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INDUSTRIAL ELECTRICAL MEASURING INSTRUMENTS

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BY

KENELM EDGCUMBE, A.M.INST.C.E. M.I.E.E.

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PREFACE

In view of the large number of publications treating of almost every other branch of electrical engineering, it seems curious that there should not be a single work in the English language dealing, in a comprehensive manner, with electrical measuring instruments. The importance of the subject is admittedly very great, and the absence of any such works must, presumably, be ascribed to the fact that it is a branch of the industry which has become so highly specialised, and yet covers so wide a field, that writers have hesitated to undertake the task.

The present volume is an attempt to remove this reproach and, at the same time, to provide what the author has been so frequently asked for, namely, a treatise giving practical details as to the construction and working of the various types of measuring instruments in general use, together with some hints on their selection and maintenance.

The subject of integrating or supply meters has already been adequately dealt with, and is, consequently, omitted from the present treatise; as also the subject of photometry, with which it is hoped to deal in a subsequent volume.

On the other hand, relays, synchronizers and lightning arresters, although not strictly speaking measuring instruments, have been included, owing to their great importance, and to the fact that the information at present available is meagre and scattered. Amongst other subjects which have been treated at some length, for the same reason, may be mentioned instrument transformers, pyrometers, oscillographs, leakage indicators, power-factor indicators, and wattmeters.

The illustrations are, in almost every case, diagrams showing working principles rather than views of the actual apparatus. Most engineers are already familiar with the outside appearance of the instruments, so that external views are unnecessary, and photographs of working parts nearly always accentuate unimportant details to the exclusion of essential features.

Wherever possible, diagrams and curves have been given in preference to formulæ. Mathematicians will doubtless deplore the almost entire absence of mathematics, but, writing as an engineer, for engineers, the author is strongly of opinion that higher mathematics would be quite out of place. He believes that the only way to get a thorough insight into any phenomenon is to obtain a clear "mental picture" of what is taking place, and that, except to the mind of the trained mathematician, a mathematical solution too often fails to bridge over that wide gulf, which separates the *abstract* from the *concrete*.

KENELM EDGCUMBE.

May, 1908.

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INDUSTRIAL ELECTRICAL MEASURING INSTRUMENTS

INTRODUCTORY

THE measurements which the electrical engineer is called upon to carry out, consist for the most part of determinations of current, voltage, or resistance, together with their derivatives, such as power, conductivity, power-factor, and so forth.

The instruments employed for this purpose fall naturally into the following classes:—

(1) Indicating.
(2) Recording.
(3) Integrating.

Of these the first two alone are dealt with in this volume.

In view of the confusion which often arises it may be well to define these terms. Indicating instruments are those in which the quantity to be measured is read off a scale. In recording instruments a continuous record is obtained, usually on a paper chart. Integrating meters give the sum total of the quantity at any instant, multiplied by time; for example, watt-hours[1] or ampere-hours. The watt-hour meter is unfortunately sometimes spoken of as a "recording watt-

[1] Mathematically expressed a watt-hour meter gives the value of $\int va\,dt$ where v and a are the instantaneous values of volts and amperes respectively.

hour meter," or even as a "recording wattmeter," whereby considerable confusion is caused.

A further subdivision of indicating instruments is possible into

(1) Deflectional pattern.

(2) Zero or "null" method pattern.

ACCURACY OF MEASUREMENT.

In specifying that a measurement is to be made with a certain accuracy (or more correctly, with a certain precision), care must be taken to distinguish between four distinct **sources of possible error** :—

1. Inherent errors of the instruments used.
2. Errors due to the method of measurement.
3. Errors of observation.
4. Mistakes on the part of the operator.

A simple measurement leading to many possible errors is, for example, the measurement of the resistance of the shunt winding of a dynamo with a Wheatstone bridge. Taking them in order, the errors of the first class might be :—

(*a*) Inaccuracy of the bridge.

(*b*) Want of sensitiveness of the galvanometer.

(*c*) Inaccuracy of the thermometer (assuming one to be used to measure the temperature of the field coil).

Under heading 2 would come :—

(*d*) Neglect of the resistance of the connecting leads and contacts.

(*e*) Difficulty of ensuring that the copper coil is at a uniform temperature throughout its length.

(*f*) Even assuming this to be the case, there still remains the difficulty of determining its temperature.

Amongst errors of observation might be :—

(*g*) Galvanometer not precisely at zero.

(*h*) Parallax in reading the thermometer.

The possibility of mistakes is almost unlimited; for example:

(*i*) Ratio plug might be in the wrong hole (so that perhaps the ratio is 10:100 when supposed to be 10:1000).

(*j*) Resistance wrongly read off.

(*k*) Mistakes in working out the result.

Thus, apart altogether from the correctness of the instrument, there are at least eight possible sources of inaccuracy. It is not probable that they would all occur, and even if they did, the chances are that some would cancel out others. The actual errors in practice might very probably amount to:—

Errors due to instruments	a, b	± 0·1 per cent.
	c	± 0·5° C.
Errors due to method ...	d	negligible if care is taken.
	e, f	± 1° C.
Errors of observation ...	g	negligible if care is taken.
	h	± 0·2° C.
Mistakes	i, j, k	negligible if care is taken.

Thus, the electrical errors come to 0·1 per cent. and the thermometer errors to 1·7° C. (or 0·65 per cent.), assuming, as is possible, that they are all in the same direction. Making, therefore, some allowance for d, g, i, j, and k, it is safe to say that such a measurement cannot be relied upon to within less than 1 per cent., and yet it is no uncommon thing to find the result given as, for example, "103·75 ohms at 15·5° C." The reading of the bridge was probably 10375 ohms, and the ratio 10 : 1000. If the galvanometer is sensitive, another figure may perhaps be estimated, and the result expressed as "103·758 ohms," or, if the observer were exceptionally conscientious, he would express it as "$103{\cdot}75_8$ ohms," thereby

indicating that the last figure was only estimated, and could not absolutely be relied on. Even if this last figure be neglected, the **implied accuracy** is ·01 in 104, or ·01 per cent., which is, as has been shown, about one-hundredth part of the possible error.

It is of great importance that records of measurements should not be given to more figures than can be actually relied upon, since such a statement as "103·75 ohms at 15·5 C." implies that, at any rate, the experimenter was confident that the value lay between 103·7 and 103·8 ohms at 15·5° C., whereas, taking possible errors into account, all that he is really confident about is that it lay between 103 and 104 ohms.

The value 103·758 or $103{\cdot}75_8$ claims what is known as "6-figure accuracy," 103·7 "4-figure accuracy," and so forth. A result written as 12·000 claims 5-figure accuracy, so that care should be taken not to write 12 as 12·0, unless it is known to lie between 11·9 and 12·1. It is, however, usual to express accuracies (or, more correctly, errors) as percentages (*e.g.*, an error of 0·1 per cent.), or as one in so many thousands (*e.g.*, an error of 0·01 per cent. is 1 in 10,000).

The **accuracy of measurement aimed at** in industrial work varies enormously. For example, in a house installation, if the insulation is known to lie between 1·5 and 2 megohms (that is to say, to within ± 14 per cent.) it will as a rule be quite sufficient. Partly, it may be, because the required minimum has been well exceeded, but also largely because the insulation resistance is known to depend so much on atmospheric conditions. Apart from standardizing instruments, probably the highest accuracy in industrial work is demanded of central station voltmeters. Such accuracies as 1 volt in 500 are sometimes asked for, and at the same time it may be specified that the instruments are to be read at a distance. To comply with the latter requirement, suppressed zeros (see p. 17) are usually demanded, a scale reading from 450 to 550 being perhaps asked for. It is forgotten in so

doing that, whereas the observation errors are reduced, those of the instrument itself are actually increased, owing to creeping of springs, friction, bending of pointers and so forth. Thus the two requirements are, to a large extent, antagonistic, and, taking all things into consideration, it is generally admitted that an accuracy of $\pm \frac{3}{4}$ per cent. is all that is ever required of a switchboard instrument.

The case of instruments intended for standardizing purposes is different, since these must possess a considerably greater accuracy than the instruments they are intended to check. Probably $\pm \frac{1}{2}$ per cent. should be the maximum inaccuracy allowed for a testing instrument for general standardizing purposes.

The following table can be taken as a **fair average of what may be expected of good commercial instruments** under normal conditions and in the hands of users possessing average experience.

	Probable max. errors per cent.[1]
Wheatstone bridge, P.O. pattern (up to 10,000 ohms)	0·1
„ „ „ „ (above „ „)	0·2
„ „ self-contained portable pattern (up to 10,000 ohms)	0·5
Wheatstone bridge, self-contained portable pattern (above 10,000 ohms)	1·0
Deflectional insulation indicator	3·0
Potentiometer (highest grade)	0·03
„ (portable form)	0·1
Moving-coil voltmeter, laboratory pattern	0·4
„ „ switchboard „	0·75
„ ammeter, laboratory „	0·5
„ „ switchboard „	1·5
Moving-iron voltmeter, switchboard pattern, with direct current	1·5

[1] See p. 9.

	Probable max. errors per cent.
Moving-iron ammeter, switchboard pattern, with direct current	2·0
Moving-iron voltmeter, laboratory pattern, with alternating current	0·5
Moving - iron ammeter, laboratory pattern, with alternating current	0·5
Moving-iron voltmeter, switchboard pattern, with alternating current	1·0
Moving-iron ammeter, switchboard pattern, with alternating current	1·5
Induction voltmeter, switchboard pattern	1·5
,, ammeter ,, ,, ...	2·0
,, wattmeter ,, ,, ...	2·5
Dynamometer voltmeter, switchboard pattern ...	0·75
,, ,, laboratory pattern ...	0·4
,, ammeter switchboard ,, ...	1·5
,, ,, laboratory ,, ...	1·0
,, wattmeter, switchboard pattern ...	1·5
,, ,, laboratory ,, ...	1·0
Hot-wire voltmeter, switchboard pattern	1·5
,, ammeter ,, ,, ...	2·0
Electrostatic voltmeter, switchboard pattern, up to 500 volts	0·8
Electrostatic voltmeter, switchboard pattern, above 500 volts	1·5
Power-factor indicator, dynamometer pattern ...	2·0
Recording voltmeter, pen and ink pattern	2·5
,, ,, inkless pattern...	1·0
,, ammeter, pen and ink pattern	2·5
,, ,, inkless pattern	1·5
,, wattmeter, pen and ink pattern... ...	3·0
,, ,, inkless pattern	2·0

From what has been said when discussing the Wheatstone bridge test, it will be clear that the accuracy of the instruments themselves is often quite swamped by **experimental errors,** and entirely erroneous conclusions consequently arrived at. For example, it is no uncommon thing for an indicating wattmeter to be checked by placing it in series with a watt-hour meter, although the temperature and other errors of the latter are possibly three times as great as those of the former. Or again, a photometer scale might be read to half a millimetre, whereas the difference between consecutive readings on the same lamp perhaps exceeds a centimetre.

It is usual, when making a measurement, to take a number of observations and to find the **mean or average value.** In doing so it must be remembered that it is only certain of the variable errors, depending perhaps on the judgment of the observer, that are "averaged out," and that any constant errors, due either to the instruments, or to the method of measurement, will remain. It is, therefore, not necessarily safe to express the result to more figures than a single observation will allow. A comparison of the various observations with their mean affords an indication of the consistency of the results, although not of their actual correctness.

In some cases a single reading may be made more accurate than the mean of a number. For example, if it is wished to find the average potential difference at the terminals of a number of dry cells with a 10-volt voltmeter, one method would be to measure the potential difference of each cell and to take the mean. Owing, however, to the fact that the readings will be very low down on the scale (less than $\frac{1}{6}$ of the range) the accuracy of measurement would be small. If, on the other hand, six cells were connected in series, the total voltage could be determined with considerable accuracy, and this value divided by six would give the required value for each cell. Even in so simple a case as this, however, there

are several possible sources of error. In the first place it will be noticed that the external resistance (that of the voltmeter) is the same whether there be one cell or six in circuit, so that the current flowing is widely different in the two cases. Again, it would be well, roughly, to test each cell separately, so as to detect any which gave abnormal readings. In expressing the result of such a test, the current flowing and the length of time the circuit had been closed before making the measurement should be stated. Even if two voltmeters were available, one of 10-volt range and the other of 2, this method would probably give the more correct result, since, if the voltmeters had an inaccuracy of ± 1 per cent., the readings would be accurate to ± 1 per cent. if each cell were tested separately, but to ± $\frac{1}{6}$ per cent. if six were tested in series. This question has been discussed at some length, not as being a test which is, in itself, likely to be often required, but as showing how many considerations must be kept in view in making the very simplest measurement.

It is often assumed that an **evenly divided scale** is the ideal to be aimed at, but, as a matter of fact, if the same

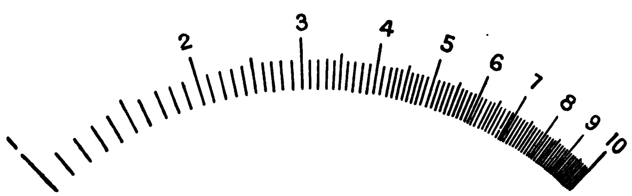


FIG. 1.—Logarithmic scale.

percentage accuracy of reading is required at all points, the divisions should be wider at the beginning than at the end of the scale. In a logarithmic scale, such as is shown in Fig. 1, which is the same as that employed on a slide rule, a given error of reading at all points entails the same percentage error. Very few instruments could, however, be given scales

approaching this, exceptions being dynamometer wattmeters, moving-iron instruments over part of their scales, and ohmmeters.

Such being the case it is not, as a rule, reasonable to expect the same percentage accuracy at all points of the scale. What might be called the "electrical accuracy" can safely be so expressed but the errors due to friction, observation, and so forth will be more or less constant, so that the errors should strictly be expressed in some such form as $p \% \pm q$. For this reason it is becoming more and more common to guarantee instruments as correct to within $\pm x$ **per cent. of the maximum scale reading.** For example, an ammeter scaled to 50 amps. and guaranteed accurate to within ± 1 per cent. of the maximum would be accurate to within ½ ampere throughout its range. It would be absurd to expect it to be correct to within 1 per cent. at a reading of, say 5 amps.

Care must be exercised when **multiplying or dividing**, and still more when squaring or cubing, a value which is only known to be accurate to a given number of figures. Take, for example, the case of a voltmeter having a scale graduated up to 120 volts, and provided with an additional resistance for 600 volts. Suppose the reading to be 106, this may very probably be known to be correct to three figures, that is to say, the true reading is known to lie between 105·5 and 106·5. After multiplying by 5, however, the value 530 may not be correct to three figures, since the actual volts may be anything between 527·5 and 532·5. For this reason it is much more satisfactory to speak of a result as being correct to within so much per cent., rather than as correct to so many figures, since the percentage accuracy is unchanged by multiplying or dividing.

The case of **squaring or raising to any power** is different. If a measurement is made to within, say, 2 per cent., and the value is squared, the result can only be relied

upon to within some 4 per cent. if it is cubed to within 6 per cent., if raised to the nth power to within $2n$ per cent. As showing how important this sometimes becomes, the case of photometers may be instanced. The candle-power of a carbon glow lamp varies usually as about the 6th power of the voltage and consequently if the voltage measurement cannot be made closer than ± 1 per cent., the candle power cannot be relied upon to within less than 6 per cent.

CONSTRUCTIONAL DETAILS.

CASES.

The form of case to be used depends chiefly upon the space available, and the purpose for which the instrument is to be employed. The more usual patterns are:—

(1) Portable wooden cases.
(2) Round switchboard cases.
(3) Sector-shaped cases.
(4) Edgwise cases.

Portable cases are most satisfactory when made of oak or teak and provided with flaps arranged to let down, which protect the glass in transit, and the modern practice is to make the case part of the instrument rather than to slip the latter into a case from which it has to be removed each time it is used.

Round switchboard instruments are sometimes supplied as large as 12 in. in diameter, but except for special purposes, such as synchronisers (see p. 124), it is preferable to restrict their use to a scale length of 6 in. or 7 in., and then to employ the **sector pattern,** which is much more economical of space. For example, a round instrument having a 9 in. scale would occupy about 14 in., whereas a 9 in. scale sector would be only some 11 in. wide. It is, moreover, easier to illuminate the dials of sector instruments, since they can conveniently be

made of opal glass or other semi-transparent material with one or more lamps behind them.

Edgwise instruments are useful when the space on the board is restricted, as is often the case with feeder ammeters. They are not, however, very satisfactory when great accuracy is demanded, owing to their liability to parallax errors.

Some years ago it was the custom to specify brass cased instruments for all high-class work, but it is now realised that iron cases well finished in black and nickel, or black and copper, are far more durable, and, moreover, protect the instrument both mechanically and magnetically.

The usual finish is a bright and hard black stove enamel, but some engineers prefer a matt surface, as being less liable to reflect the light and so distract the eye when taking a reading.

SCALES.[1]

Hardly sufficient attention is directed either to the marking of the scale or to the shape of the pointer. **Silvered brass scales** were at one time asked for, but, as may be imagined, it is not easy to obtain any great accuracy by this means, since the divisions have first to be marked off by hand and afterwards cut on an engraving machine. A step in advance, as regards accuracy, though not permanency, lay in the substitution of hand painting for engraving. **Enamelled metal scales** have the same disadvantages, added to which the enamel is liable to crack, and even to flake off after a time, especially in hot climates. It is now fully recognised that, all things considered, a scale carefully drawn out on a good surface **card, mounted on metal,** is by far the most satisfactory. In preparing it, readings are first taken on a scale divided in degrees fitted to the instrument, and a curve is plotted connecting amperes (say) and deflection in degrees. From this curve the actual scale is drawn in Indian ink by means

[1] See also p. 8.

of a special scale-drawing mechanism. In this way the highest possible accuracy is attainable.

For laboratory use instruments should have finely divided scales (though divisions of less than 0·5 mm. are not to be recommended), and the pointers may be bent up on edge so as to present an extremely fine line to the eye. Under the scale must be fixed a mirror to avoid parallax. This is usually of silvered glass, though occasionally polished metal is employed.

The **numbering** should be small and at short intervals, and, where several ranges are to be read off the same scale, it is convenient to indicate the values of the main divisions for each range. This is preferable to printing two or more distinct sets of divisions, and for this reason the ranges chosen should form convenient multiples of one another. For example, 1, 10, 100, etc., or 1, 5, 25, etc. In the case of instruments having evenly divided scales, each range can conveniently be made $\frac{1}{10}$th of the next higher, unless extreme accuracy is required, when $\frac{1}{5}$th is preferable. For scales which are cramped at the lower end, such as moving-iron or hot-wire instruments, less than $\frac{1}{5}$th is inadmissible.

For switchboard instruments, which have, as a rule, to be seen from a distance, and often in a bad light, finely divided scales are not only unnecessary but misleading. Bold divisions, ranging from $\frac{1}{16}$ in. to $\frac{1}{4}$ in. apart, the thickness of the main divisions being probably greater than that of the rest, should be insisted on. The pointer also must be broad throughout its length, and be provided with a spear-shaped end, terminating in a fine point by means of which accurate readings can be taken, when it is possible to observe the instrument from close by.

The number of divisions in the scale of a switchboard instrument would range from 50 to 100, and the unit selected per division is of considerable importance. The ideal condition

is clearly that the smallest subdivisions should represent 1, 10, 100, etc., units, which, however, can seldom be the case. Next to this, 5, 50, etc., is the most satisfactory, then 2, 20, etc., while 4, 40, etc., is not so good, since it is less easy to count by fours. 2·5, 25, etc., also may be useful, but no other units should be used if it can possibly be avoided.

INSULATION.

The problem of insulating the winding from the case is a most important, and at the same time a most difficult one. It is no longer customary to carry currents at pressures exceeding, say, 750 volts to the instrument itself, although at one time such instruments were constructed up to 2,000 or 3,000 volts, and for this purpose cases of ebonite or other insulating material were employed. Modern practice, however, very rightly demands that the case shall be of metal, **efficiently earthed,** so that, even if the insulation of the instrument breaks down, no danger can be incurred by touching the case.

An exception is made of electrostatic voltmeters for pressures of 3,000 volts and over, which are, as a rule, fixed high up on the board in insulating cases, protected by fuses and high resistances (see p. 88). Since the high tension must be led into the instrument itself (unless condensers are used, see p. 90), the case, if of metal, would have to be made very large to preclude sparking across.

The insulation of instruments intended for use in **hot and damp climates** is a matter requiring great care. Mica should be used whenever possible, and if fibre is employed it must be specially impregnated and varnished. Press-board (*press-pan*) is to be avoided as it becomes distorted with damp. The case should be made as air-tight as possible, and the packing used for the purpose must be insect-proof. Metal

dials are usually called for, but, if properly fixed, card scales are perfectly satisfactory.

All instruments should be tested to at least 50 per cent. greater pressure than that at which they will be worked. Low-tension instruments are usually **tested** to 1,000 or 1,500 volts, and high-tension instruments to 50 per cent. more than the working pressure. Excessive pressure tests of 2,000 or 3,000 volts are not only unnecessary. but actually harmful since the insulation is thereby needlessly strained, and ma even be permanently damaged. In the case of transform the test applies to the insulation between the primary of transformer and the secondary or core, the instrument itse being tested to, say, 1,000 volts.

CONTROLLING SPRINGS AND WEIGHTS.

The controlling force in modern instruments is almost always either gravity or a spring. In the cheaper instruments of the moving-iron pattern, gravity control is usually employed, whereas for switchboard use a spring control is much to be preferred, owing to the difficulty which is experienced in setting a number of instruments absolutely level on a board. Fig. 2 shows a typical arrangement of controlling and balancing weights in a "**gravity** instrument." In the position shown the pointer P would be at the zero of the scale, and the full deflection will take it to P', the angle θ being, as a rule, about 80°. The moving-iron at C is balanced by P and B, or, if there is

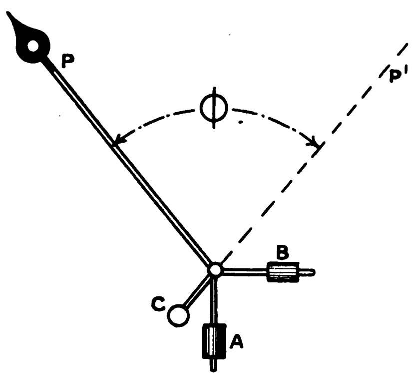


FIG. 2.—Balance and control weights of gravity instrument.

any resultant, it is in line with the weight A (*i.e.*, vertically up or down). Consequently, any adjustment of A will not alter the zero position, but will proportionately affect the **torque** at all points on the scale.

As the pointer is deflected, the weight takes up successive positions such as a, b, c, etc., in Fig. 3, the torque at each point being equal to the weight multiplied by o, $b\ b'$, $c\ c'$ and $d\ d'$ respectively. It will be noticed that the control increases more rapidly at first than towards the end of its travel. The torque is in fact proportional to the sine of the angle of deflection. In the case of a **spring control** on the other hand, the torque is directly proportional to the angle of deflection. This difference is shown in Fig. 4, in which curve II shows a gravity control and curve I a spring control. The torque at the end of the travel (80° deflection) is the same but the weight exerts a greater torque at all other points. The effect on the scale is not very marked, but a moving-iron instrument gives a rather more open scale at the lower end when spring-controlled than when gravity-controlled.

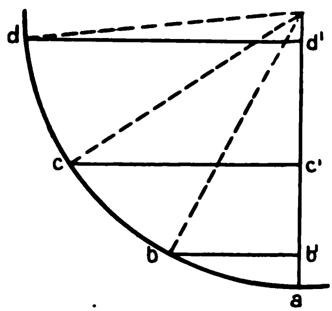


FIG. 3.—Control due to a weight at various angles.

It should be remembered, in connection with controlling or balancing weights, that if w is the weight and r is distance from the centre, then:—

Torque is proportional to $w\ r$

Weight on pivots is proportional to w

Momentum is proportional to $w\ r^2$.

Hence for a given torque we have

Weight on pivots proportional to $\frac{1}{r}$

Momentum proportional to r.

Thus it follows that, as far as friction is concerned, the weight should be at the end of a fairly long arm, but that considerations of damping prevent this being carried too far.

The **design of control springs** demands very great care if permanent accuracy is aimed at. It is well known that if any

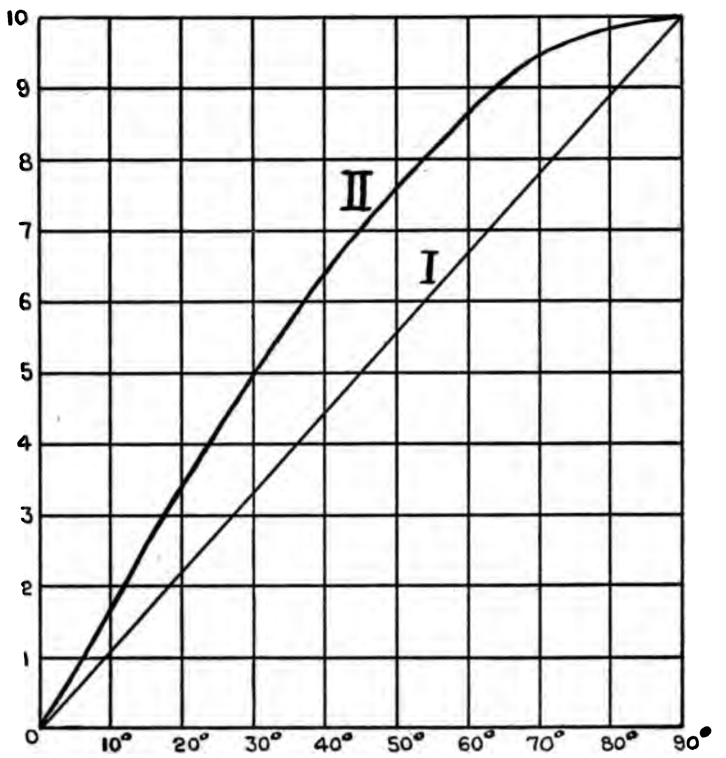


FIG. 4.—Spring and gravity control compared.

material is bent or twisted beyond a certain point it will be permanently, or sub-permanently, deflected after the bending force has been removed. This shows itself in measuring instruments by a failure to return to zero after prolonged deflection. This "zero error" must not however be confused with the effect of a thermo-E.M.F. (see p. 25). Readjusting to

zero does not get over the difficulty, since after standing for some time, the spring will probably almost regain its normal shape, and the cycle will recommence as soon as the current is again switched on.

Taking the case of the ordinary spiral spring, such as is used in measuring instruments, there is, for a given length of spring and a given angular deflection (say 90°) a maximum thickness which it is unsafe to exceed. If greater strength is required the width must be increased. The torque exerted by such a spring is given by the formula

$$T = \frac{E\,b\,t^3\,\theta}{\cdot 6875\,l}$$

where T is the torque in gramme-centimetres; t the thickness of the spring, b its breadth, and l its length, all in centimetres; θ is the angle in degrees through which the free end is deflected; E is what is known as the "modulus of elasticity" (in kg. per square cm.) and is a constant depending upon the material. For phosphor-bronze, such as is used for springs, E may be taken as 1,150,000.

When such a spring is bent, the material along what may be called the "neutral axis" is unstrained, while that outside it is extended, and that inside it is compressed. The thicker the material the greater will be these forces. The stress experienced is, in fact, equal to $\frac{6\,T}{bt^2}$ gramme centimetres, and it is found from experience that this quantity must not exceed about 600 kg. per square cm.

Assuming a deflection of 90° it can be shown, by combining the two formulae just given, that the **length of a spring must be at least 1500 times its thickness.** In the case of suppressed zero instruments the angular deflection or "set-up" will be greatly in excess of 90° and the difficulty of obtaining sufficient strength, without exceeding the allowable ratio of length to thickness, becomes greater. For

example, a scale of 500 to 600 volts entails a spring set-up through 540° at its maximum deflection (assuming a 90° scale) so that the length must be $1{,}500 \times \frac{540}{90}$ or 9,000 times the thickness.

A spring for a moving-iron voltmeter might have the following dimensions :—

$$t = \cdot 006 \text{ in.}, \; b = \cdot 03 \text{ in.}, \; l = 15 \text{ in., hence } \frac{l}{t} = 2{,}500.$$

Such a spring would serve perfectly well for a free zero instrument, as has been seen, but would be quite unsuitable for the 500—600 volt range. In fact, the permissible maximum set-up with this spring would be, say, 40 %, *e.g.*, 60—100 volts.

The **strength of a spring**, or the torque exerted per degree deflection, can be **measured** in two ways. The simplest is to attach the spring to a lightly pivoted horizontal spindle carrying a carefully counterbalanced pointer. The position of rest of the pointer with the spring undeflected is observed, and a known weight (g grammes) is then hung on the pointer at a given distance (l cm.) from the centre. The angle ($\theta°$), through which the free end of the spring has to be turned to bring the pointer back to its former position is then noted. The strength of the spring in gramme-centimetres per degree is $\frac{g\,l}{\theta}$.

A somewhat more accurate, though less convenient method is to attach the spring to a very finely pivoted fly-wheel; one of about the weight of a penny being very satisfactory. The time occupied in making 10 swings is noted, and is inversely proportional to the square root of the strength of the spring.

At one time it was usual to employ two springs wound in opposite directions with a view to eliminating any error due to expansion or contraction with temperature, and these springs formed a convenient means of leading the current

into the winding. The temperature error in question is, however, quite negligible, and most makers now employ one spring only, and lead the current in by means of silver or copper strips exerting as small a torque as possible.

A further advantage of this arrangement is that the **resistance** of these ligaments is considerably smaller than that of the springs. In the case of voltmeters this is of small importance, but for ammeters it is essential that the resistance should be small, since, added to that of the coil, it forms a determining factor in the matter of temperature errors. As has been seen the torque is proportional to $\frac{bt^3}{l}$, but the conductivity is proportional to $\frac{bt}{l}$. Hence it follows that for a given strength the thinner the material the lower the resistance.

In order to increase the **conductivity of springs**, alloys of silver and copper have been tried, but are all more or less liable to deformation and have been abandoned.

PIVOTING.

Of all the mechanical parts of an instrument, the most important and, at the same time, the most liable to derangement, are the pivots. Various devices have been tried, such as friction-wheels, knife-edges, needle-points working in hardened cups, and suspending ligaments, but, with the exception of the last two, all have been abandoned in favour of steel points in sapphire or agate **jewels.** Of these, agates are the harder, but more liable to crack, so that, for heavy movements, and more especially those subjected to vibration or rough usage, sapphires should always be employed.

Some divergence of opinion exists as to the best **form of pivot** and jewel. For laboratory instruments, subject to little rough usage, a fine point will be found best, while

for commercial work a more obtuse angle is to be preferred as being more durable. The pivoting is always better in instruments in which the pointer swings in a horizontal plane, since nearly all the weight is then carried on one point which rests on the bottom of its jewel. The more nearly the axis approaches the vertical the less will be the friction. In order to ensure this the system may be supported on one pivot only (see p. 57).

For switchboard instruments, however, it is, as a rule, necessary that the pointer should move in a vertical plane and for some instruments, such as electrostatic voltmeters, in which the working forces are small, the ordinary pivoting is unsatisfactory. Needle points resting on hardened steel cups (see [. 5) are often used and are quite durable so long as vision is made for lifting them when travelling, and pro- ed the instrument is not subject to frequent and sudden loads.

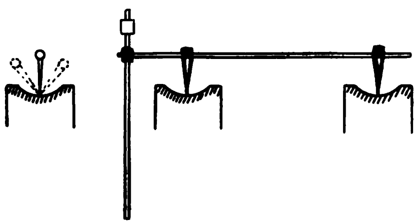


FIG. 5.—Needle-point pivoting.

PERMANENT MAGNETS.

In nearly all instruments in which permanent magnets are nployed, the requirements are maximum **strength of field** sistent with permanence. As regards the former, the le lines of force can be calculated in much the same in the case of a dynamo or motor. The subject is of portance in instrument design, but is, as a rule, not in text-books on magnetism.

of hard steel is magnetised by winding round it a ns of wire, carrying a current, the magnetisation omething like that shown in Fig. 6, the abscissae

representing ampere-turns per centimetre length of magnet, and the ordinates the induction in lines of force per square centimetre of cross-section. As the current is increased, B at first rises rapidly and then more and more slowly. If the magnetising ampere-turns are now gradually reduced, B will fall, but when the current is zero the induction will still have a value Bp. The steel is, in fact, permanently magnetised. If the direction of the current is now reversed so as to demagnetise the steel, it will take a demagnetising force (in ampere-turns per centimetre length) equal to $O\ Hp$ to demagnetise it

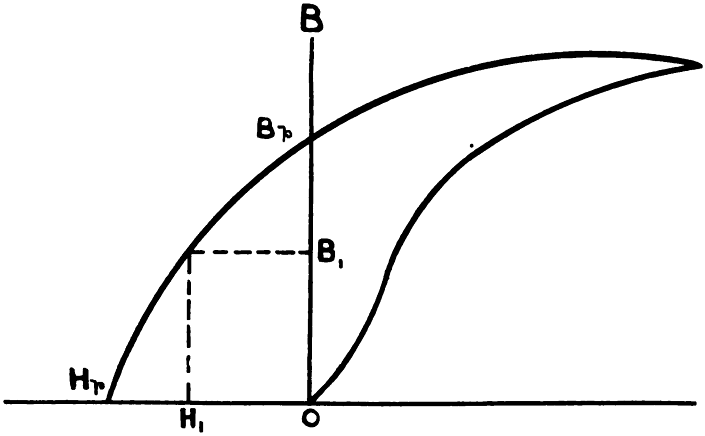


FIG. 6.—Magnetisation curve of a permanent magnet.

completely. That is to say, the steel ring possessed a magnetomotive force of its own equivalent to $O\ Hp$ per cm. This m.m.f. was moreover sufficient to maintain an induction Bp in the steel.

If now, a saw-cut be made in the steel, so as to introduce an air-gap, the induction density will at once fall (say to B_1) since part of the available m.m.f. is now required for the air-gap. The portion $H_1\ O$ is, in fact, available for this latter purpose, while $Hp\ H_1$ is required to send the lines through the iron.

It is thus possible, if the magnetisation curve of the steel is known, to predetermine with very fair accuracy the size of magnet necessary to give the required number of lines in the air-gap. The area of the magnet must first be so chosen as to give a suitable induction (B_1) in the steel, say 2,500 to 3,500 lines per square cm. The value of the m.m.f. necessary to produce this induction can then be read off the curve ($Hp\ H_1$), and consequently also the magnetising force per cm. still available for the air-gap ($H_1\ O$). If H ampere-turns are required for the air-gap[1] the necessary length of magnet will be $\frac{H}{OH_1}$.

In this calculation the reluctance of the pole pieces, and also any magnetic leakage, have been neglected, so that both the area and length should be made slightly greater than their calculated values, to allow for this.

If it is desired to increase the number of lines of force in a given instrument by, say, 20 per cent., the sectional area of the magnet must be increased by 20 per cent., so as to keep the induction the same, and its length by 20 per cent., so as to provide the additional 20 per cent. of magnetising force for the air-gap. Roughly speaking, it may be said that, other things being equal, the induction density in the air-gap will be proportional to the volume of the magnet, and lies, usually, between 800 and 2,000 lines per sq. cm. If, on the other hand, it is wished to obtain the same induction with a longer air-gap, the length of the magnet should be increased. The same result might be arrived at by increasing the sectional area, so as to reduce B and, consequently, increase $H_1\ O$, but this is not so satisfactory from the point of view of permanence. In general, the greater the ratio $\frac{Hp\ H_1}{Hp\ O}$, the better will

[1] The number of ampere-turns necessary to produce an induction B in air is 0·8 B for each centimetre of length.

be the keeping properties of the magnet. This consideration leads to an air-gap of large area and small length.

There are various **steels** on the market which have been specially prepared for permanent-magnet making, and the most suitable hardening process for each has been worked out, so that the choice of material is a fairly wide one.

The **magnetisation** is, as a rule, carried out by means of a powerful electro-magnet, across the poles of which the steel is laid. It is found best to make and break the circuit several times before the magnet is finally removed. Sometimes, particularly in the case of damping magnets, the poles are so close that it is difficult, owing to magnetic leakage across the narrow air-gap, to force sufficient lines through the steel. This can be, to some extent, remedied by rapidly rotating a copper disc between the poles of the magnet. The leakage lines induce eddy currents in this disc, and these tend to oppose and weaken the leakage field.

The magnets, after being hardened and magnetised, are **artificially "aged."** The process varies with different makers, but usually consists in raising the magnets to a fairly high temperature (say 60° or 100° C.) for from 6 to 48 hours, and subsequently subjecting them to mechanical vibration. Both these processes somewhat reduce the induction, and are intended to bring about the same result in the magnet as prolonged use under ordinary conditions. Some makers even go so far as to demagnetise (to the extent of say 10 per cent.).

It has recently been proposed by Mr. B. O. Pierce,[1] of Harvard, U.S.A., to employ **hardened cast-iron for magnets,** and as the result of experiments undertaken by him in America, and by Mr. Albert Campbell[2] in this country, there would certainly

[1] *Am. Acad. Proc.* xl. 22, p. 701 (April, 1905), and *Electrical Review* (N. Y.), September 15th, 1905, p. 411 ; see also paper by Ashworth, *Proc. Roy. Soc.*, lxii., p. 210 (1897).

[2] Paper read before Physical Society of London, January 26th, 1906.

appear to be a promising field for such magnets, although the data at present available are somewhat meagre.

Ordinary grey cast-iron is employed, and is suddenly cooled in water from near its melting point (say from 1,000° C.). Extreme care is necessary in handling, owing to the brittle nature of cast-iron at this high temperature. From tests made by the two experimenters just mentioned, the maximum remanence of magnets so prepared averages some 30 per cent. less and the coercivity some 20 per cent. less than that obtained with first-class magnet steel. According to Pierce, the deleterious effects of time, vibration &c., would appear to be no greater than in the case of corresponding steel magnets.

AMMETER SHUNTS.

In almost all cases the **essential features** of a shunt are constancy of resistance at all temperatures, good heat dissipation, and absence of thermo-E.M.F.'s at the terminals. The heat to be dissipated by the shunt may be very considerable if the instrument connected to it demands a high potential difference at its terminals. This varies, as a rule, from 0·05 volt to 0·5 volt, but in the case of potentiometers it may reach 1·5 volts at full load. The necessary resistance of the shunt is $\dfrac{\text{full load voltage drop}}{\text{full load current}}$ and the heat to be dissipated in watts = amperes × voltage drop.

The **materials most used** for the construction of shunts are manganin (84 copper, 12 manganese, 4 nickel), whose temperature coefficient is 0·0005 per cent., and its resistance about 25 times that of copper, and constantan (60 copper, 40 nickel), with a temperature coefficient of —0·001 per cent., and a resistance 30 times that of copper. Of these, constantan is the more readily soldered and is less liable to deterioration through heat or surroundings, but has, unfortunately, a somewhat high **thermo-E.M.F.** with copper, namely, 0·0037 volt

per 100° C. As it is extremely difficult to ensure that the two shunt terminals shall be always at the same temperature, the indications of the ammeter, which is in reality acting as a milli-voltmeter, may be thereby considerably disturbed.

The presence of an error due to this cause can be detected by breaking the main circuit, when it will be noticed that the pointer, instead of returning to zero, shows a slight deflection to one side or the other, and only gradually returns to zero as the shunt cools down. The ammeter reading should be corrected by adding or subtracting, as the case may be, the deflection so observed immediately after opening the circuit. The error can be entirely eliminated by connecting the leads from the instrument, not to the shunt-blocks direct, but to the ends of two strips or wires made of the same metal as the shunt.

This arrangement is shown on Fig. 35 (p. 76). If the strips *a c* and *b d* are sufficiently long and thin to ensure the points *c* and *d*, being always at the same temperature (*i.e.*, that of the surrounding atmosphere) independently of the temperature of *a* and *b*, it is clear that no thermo-E.M.F. is possible. The points of attachment (*a* and *b*) need not necessarily be on the leaves of the shunt, but can be on the shunt-blocks, assuming, as will almost always be the case, that the temperature of *a* and *b* is the same as that of the respective points of junction between the leaves and the blocks. When this is so the two equal and opposite thermo-E.M.F.'s will cancel each other.

Shunts are usually constructed of thin sheet, say 0·5 mm. thick, and varying in width according to the current. In order to make the whole as compact as possible, the sheet is cut up into a number of strips which are placed one above the other, with an air-space between them, as indicated in Fig. 36 (p. 76), which shows a typical shunt. One or two firms have employed wire in place of sheet, but have in almost every case abandoned it in favour of the latter.

The end blocks are usually of copper, and so arranged that the conductors or 'bus-bars can be clamped on each side, if required, so as to ensure ample contact surface. This is a matter of considerable importance, since it is found that the cooling of a shunt depends largely on the heat dissipated by means of the conductors, in fact, almost more so than on the cooling surface of the shunt plates themselves.

CALCULATION OF WINDINGS.

With a given design of moving system there is always a **minimum torque** corresponding to full deflection, below which it is unsafe to go, owing to frictional troubles. With any instrument the greater the working forces the more satisfactory will it be, and it is an unwise policy to demand an abnormally low power consumption unless there is good reason for so doing, since this usually means small working forces.

It may be said, in a general way, that the ratio of torque in gramme-centimetres to weight in grammes, should not be less than 0·1. For example, if the weight of the moving parts of a certain instrument is 3 grammes, the torque at full deflection should not be less than $3 \times 0{\cdot}1 = 0{\cdot}3$ gramme-centimetres. These figures only apply to carefully jewelled movements; with recording instruments (p. 147) the working forces must be very much increased, say to 10 gramme-centimetres.

Having decided upon the necessary torque, the winding must be so designed as to give this, with minimum **power consumption.** In the case of voltmeters it is the current which has to be kept down, whereas with ammeters it is the voltage drop. Again, in alternating-current instruments self-induction has to be reckoned with (see p. 30). The necessary **ampere-turns** must first be determined, for a given type, by calculation or experiment, and individual instruments of the same pattern will be found to differ but little amongst

themselves, if the various parts are made on the interchangeable system. The following figures may be taken as a rough guide. In the case of dynamometer instruments it must be remembered that it is the product of the ampere-turns of the fixed and moving coils that determines the torque.

Type of instrument.	Ampere-turns.
Moving-iron ammeter or voltmeter	300 to 500 (90° deflection).
Moving-coil ,, ,,	·3 to 1 ,,
Induction ,, ,,	300 to 500 (300° deflection).
Dynamometer wattmeter	
moving coil	20 to 40 } (90° deflection).
fixed coil	500 to 1,000 } (90° deflection).

One of the simplest windings to calculate is that of an **ammeter coil** such as would be used for a moving-iron instrument. Having decided upon the allowable size of bobbin, it has to be filled with wire or cable of suitable size to carry the current, allowing say 1,000 amps. per square inch sectional area. For heavy currents strip-wound or cast coils are often employed. If the ampere-turns so obtained are insufficient, either a larger bobbin or smaller wire must be used. As a guide to the size of the latter, it may be said that the surface area of the finished coil should be about 2 square inches for each watt dissipated in heat. In calculating this the circumference of the coil multiplied by its length is taken as the surface area.

The case of a **voltmeter** is somewhat more complicated. The necessary ampere-turns must be obtained without an excessive current, and, at the same time, the resistance of the coil should not exceed, say, 20 per cent. of the total resistance of the instrument, with a view to keeping down the temperature error. For example, in a moving-iron voltmeter, the

size of bobbin and also the required number of ampere-turns being known, the area of the wire can be calculated from the formula

$$\text{Area} = \frac{\text{mean length of each turn} \times \text{ampere-turns} \times 78}{\text{volts across coil} \times 10^8},$$

all dimensions being in inches.

The diameter of a wire with the required area can be found from a wire table and its covered diameter determined. For wires varying from No. 40 S.W.G. to No. 20 S.W.G. the following amounts should be added to the respective bare diameters:—single cotton and double silk coverings, 0·004 in. to 0·006 in., and for a double cotton covering, 0·007 in. to 0·01 in. This diameter, divided into the length of the bobbin, gives the turns per layer, and divided into the depth of the winding, gives the number of layers. Thus the total number of turns is known, and this number, divided into the ampere-turns, gives the current which the instrument will take. If this current is excessive, the volts across the coil itself must be increased; that is to say, the idle resistance must be reduced. On the other hand, the watts expended in the coil itself (*i.e.*, amperes × volts across it) are found to be independent of the area of the wire used, and consequently of the current taken. The watts per square inch of surface, calculated as explained on p. 27, should not exceed 0·3.

Neglecting the space occupied by the insulation, which can safely be done where only small changes of size are concerned, and assuming **a given bobbin** to be, in every case, **wound full of wire, the following relations hold good**, A being the sectional area of the wire or cable forming the winding:—

In any coil:—

$$\text{Number of turns} \propto \frac{1}{A}.$$

$$\text{Resistance} \propto \frac{1}{A^2}.$$

In an ammeter coil:—

Ampere-turns (with a given current) $\propto \frac{1}{A}$.

Voltage drop[1] (with a given current) $\propto \frac{1}{A^2}$.

Current (for a given number of ampere-turns) $\propto A$.

Voltage drop (for a given number of ampere-turns) $\propto \frac{1}{A}$.

Assuming constant ampere-turns, the voltage drop will be inversely proportional to the current; while the current density and the power consumed will be independent of the range. Thus a 100 ampere ammeter will have half the drop of a 50 ampere instrument, but will consume the same power.

In a voltmeter coil:—

Ampere-turns $\propto A$ at a given terminal voltage.

Current taken $\propto A^2$ at a given terminal voltage.

In the case of **pivoted or suspended coils** (*e.g.*, those of permanent-magnet or dynamometer instruments) the problem is further complicated by (1) considerations of weight, and (2) the resistance of the leading-in springs or strips (see p. 19).

The question of weight is, as a rule, settled once for all by the design of coil, since, whether it is wound full of fine or coarse wire, the weight will not vary appreciably. The resistance of the leading-in strips is usually negligible in the case of voltmeter coils, so that the same considerations hold good with these as for the fixed voltmeter coils just considered.

With moving-coil ammeter windings, on the other hand, as larger and larger wire is used, the voltage drop across the coil falls proportionately, but the resistance of the leading-in strips remaining constant, the *total* drop gradually falls to a

[1] The ohmic drop is here considered, but since the flux is always constant as well as the ampere-turns the formulae apply equally to inductances (see p. 30).

minimum value, and then again rises owing to the increasing current. It will be found that this minimum point is reached when the resistance of the winding is half that of the leading-in strips, that is to say is one-third of the total. Owing to the very small winding depth in a moving-coil instrument, the size of wire which should give the best results may not be of suitable diameter for winding in one or even in two or more layers, and a different size must be chosen. It is frequently useful for this reason to wind the coils in two parts and to join them in parallel.

It is preferable that the total resistance of a shunted instrument should not be less than 1 ohm, in order to avoid errors due to bad contacts and slight differences in the size and length of the leads used to connect the instrument to the shunt. To minimise temperature errors a resistance of at least four times that of the copper (including coil, springs and connecting wires) should be joined in series with the coil itself.

In calculating the windings of **alternating current instruments**, self-induction and capacity have to be reckoned with, and this question often becomes of extreme importance, particularly in the case of wattmeters (see p. 101). In any coil, if the current is kept constant, the self-induced voltage is roughly proportional to N^2, where N is the number of turns. If, on the other hand, the ampere-turns are kept constant, the self-induced voltage will be proportional to N, and the ohmic drop being also proportional to N (see p. 29), the angle of lag will be constant, and the impedence proportional to N.

It was at one time the custom to wind **non-inductive resistances** in two parallels, the current flowing through the two wires in opposite directions. By this means self-induction could be entirely eliminated, but the chances of breakdown were great, owing to the fact that the full potential difference existed between two adjacent wires, and, for the same reason,

the capacity was comparatively high. Both disadvantages, however, can be removed by winding the resistance in sections. The capacity of a resistance consisting of n sections is $\frac{1}{n^2}$ times that of one wound in a single coil; moreover the maximum difference of potential between neighbouring wires is $\frac{1}{n}$ of the full voltage. In modern practice, however, double wound resistances are seldom used, and self-induction is eliminated by winding the coil on a flat card or frame, either continuously or in sections. The cooling surface is then a maximum and the capacity negligible.

In some simple cases, the **self-induction of coils without iron cores**[1] can be calculated from their dimensions, but where the shape is complicated it is preferably measured in one case, and with that particular shape and size of coil the self-induction can in future be readily calculated, being directly proportional to the square of the number of turns.

Infinitely long solenoid with one layer of wire :—

$$L = \frac{4\ \pi^2\ N^2\ r^2}{l \times 10^6} = \frac{(\text{length of wire})^2}{l \times 10^6}\ \text{millihenry}.$$

r is the radius of the coil, l its length (assumed to be so long that the effect of the ends can be neglected), all dimensions being in centimetres, and N the number of turns.

Long cylindrical solenoid evenly wound :—

$$L = \frac{4}{3}\ \pi^2\ \frac{N^4}{l^3 \times 10^6}\ (R - r)\ (R^3 - r^3)\ \text{millihenry}.$$

R is the outer radius of the coil, and r the inner.

Round coil of circular cross-section :—

$$L = \frac{4\ \pi\ N^2}{10^6}\ (R - \sqrt{R^2 - r^2})\ \text{millihenry},$$

[1] For coils with iron cores, see choking-coils, p. 32.

where R is the mean radius of the coil, and r the radius of its cross-section.

CHOKING-COILS.

In a great many alternating current instruments choking-coils (often spoken of as impedence or reactance coils) are employed, and as their construction is dealt with in but few text-books, it may be well to go into the question here.

Such coils are generally used for **one of two purposes**; either to produce a certain angle of lag between voltage and current, or to absorb a given voltage. They may have either open or partially closed magnetic circuits, the former being shown in Fig. 7 and the latter in Fig. 8. In either case the

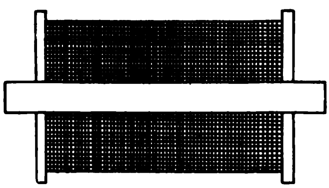


FIG. 7.—Open circuit choking-coil.

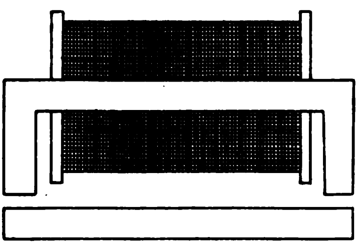


FIG. 8.—Partially closed circuit choking-coil.

object is the same, namely, to produce a maximum choking effect at a given current with the smallest possible expenditure of power. As the magnetic circuit is made more and more closed, the copper loss decreases, while the iron loss increases, so that a compromise has to be made, and a nearly closed iron circuit, such as that shown in Fig. 8, will be found to give the best results. The small air-gap, moreover, enables any required adjustment to be made.

If a choking-coil and a non-inductive resistance are connected in series across a voltage V, the potential differences at the terminals (v_i and v_n respectively) will be given by the equation :—

$$V^2 = V_i^2 + V_n^2,$$

since they are practically 90° out of phase with one another.

The method to be followed in **calculating the winding** of a choking-coil is as follows :—

(1) Determine, tentatively, the total flux, assuming an induction $\mathbf{B} = 10{,}000$ lines per sq. cm.

(2) Determine the required number of turns from the formula :—

Induced volts

$$= \frac{\text{flux (maximum value)} \times 4{\cdot}44 \times \text{turns} \times \text{frequency}}{10^8}.$$

(3) This number, multiplied by $\sqrt{2}$ and by the current in amperes which the coil is to pass, represents the available ampere-turns (maximum value).

(4) The ampere-turns required for the iron can usually be neglected, compared with those required for the air-gap, so that the permissible length of air-gap can be calculated thus :—

Length of air-gap (total)

$$= \frac{\text{ampere-turns (maximum)} \times \text{effective area of air-gap}}{\text{flux (maximum value)} \times 0{\cdot}8}.$$

Experience will show whether this length is satisfactory, and also whether the required number of turns can be got on to a bobbin of suitable size without over-heating. If a coil of similar design has not been constructed before, a few trial calculations should be made.

If the coil is of the type shown in Fig. 7, the air-gap ampere-turns cannot be calculated as in (4) above, since the area of the air-gap is indefinite. An approximate empirical formula[1] can, however, be used to determine the ampere-turns required for the return path through the air :—

$$\text{Ampere-turns (R.M.S. value)} = \text{flux (R.M.S. value)} \times \frac{0{\cdot}125}{\sqrt{A}}.$$

where A is the sum of the superficial areas, in square inches, of

[1] Evershed, *Electrician*, March 6th, and April 17th, 1891.

the two exposed ends of the iron core. It is thus best to allow the core to project well at each end (say not less than 20 per cent. of the length of the coil), while the length of the coil is unimportant, and is determined by considerations of heating.

If a large range of adjustment is required in a choking-coil, an open-circuit coil (Fig. 7) with a removable core projecting well (say 25 per cent. of its total length) at each end, will be found best. Moreover, the longer the coil, and the smaller the central hole, the greater will be the range of adjustment obtainable by gradually withdrawing the iron.

DAMPING.

The question of dead-beatness is somewhat complex, since it is governed, not only by the amount of damping applied, but also by the moment of inertia of the moving system, as well as by the controlling force acting upon it.

If an undamped instrument is set swinging it will oscillate on either side of its point of rest, the **amplitude and time of swing** being constant (Curve 1 in the left half of Fig. 9). If it is now slightly damped (by eddy currents, for example), the time of swing will again be constant, but will be greater than before, and the amplitude of each succeeding swing will be a constant fraction of the one preceding it (Curves 2 and 3). As the damping is increased, the "periodic time" becomes greater and greater, until, at length, it reaches a value such that the needle no longer flies past the point of rest, but stops at it (Curve 4). The motion is then said to be "aperiodic," and an instrument, just damped to this extent, is said to be **"critically damped," or "dead-beat"** in the strictest sense of the word. If the damping is still further increased the instrument becomes sluggish (Curve 5).

In the left-hand curves of Fig. 9 the moment of inertia and the controlling force are assumed constant, the damping alone

ȝ varied. This is what usually occurs in practice, since the momentum and the working forces are fixed, once for all, by various considerations, and the damping has ꞉ adjusted accordingly.

ɔomparison of the curves will show that the pointer comes to in the shortest time when critically damped. This is ys the case with any given system, but it is a condition h cannot always be attained in practice, and it will be

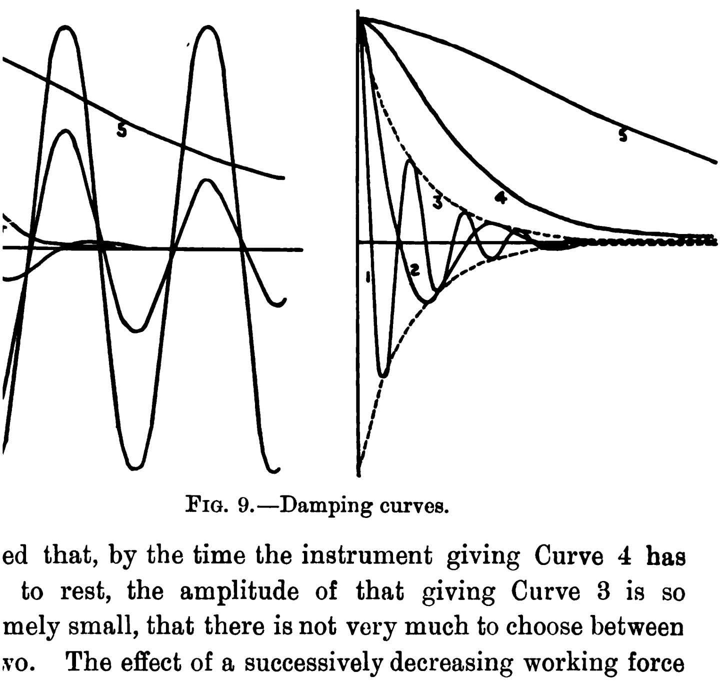


FIG. 9.—Damping curves.

ed that, by the time the instrument giving Curve 4 has to rest, the amplitude of that giving Curve 3 is so mely small, that there is not very much to choose between ᴠo. The effect of a successively decreasing working force ɔwn in the right-hand curves of Fig. 9 (1 to 4), from which l be seen that, for a given amount of damping, there is ᵞs a particular control which gives critical damping; if ꞉ed below this the movement becomes sluggish.

is easy to determine how nearly a given instrument ɔaches the point of critical damping, by noting how much

the pointer overshoots a reading as it flies up to it. This distance, divided into that between zero and the reading, is often called the "**coefficient of damping.**" For most purposes, however, what is required of an instrument is that it should accurately follow rapid variations in current; and, except perhaps in the case of a recorder, a slight overshooting of the correct reading is of small importance compared with what might be called "snappishness" of action; in fact, an instrument which is critically damped labours under the disadvantage that it is difficult to detect possible fractional errors.

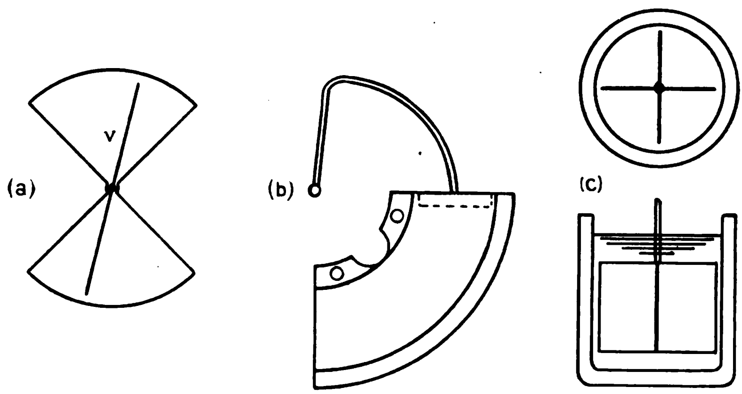


FIG. 10.—Three damping devices.

Consequently, all things considered, the best criterion is probably the **time taken in coming to rest** at a given point. The moment at which the pointer finally comes to rest is, however, somewhat indefinite, and it is easier to measure the time taken for the amplitude to fall to, say, 1 per cent. of its original value. This is easily determined, and forms a ready means of comparing the effectiveness of the damping in various instruments.

The following table gives some figures showing the **results obtained in practice** with instruments of various kinds, some being air-damped, and others damped by means of

eddy-currents. The measurements are in each case taken at a point 70 per cent. up the scale, the pointer being suddenly brought up to it from zero, by switching on a current corresponding to that reading :—

Damping.	Percentage by which the 70 per cent. mark is overshot.	Time taken in coming to rest at this point.
A. (Eddies) ...	3·5 per cent.	1 second
B. (Eddies) ...	22·5 "	2 seconds
C. (Air) ...	43 "	2 "
D. (Air) ...	10 "	2·25 "
E. (Air) ...	25 "	3·5 "
F. (Eddies) ...	51 "	6 "
G. (Air) ...	44 "	6½ "

In the above table, the first instrument is probably about as satisfactorily damped as could be wished, and is a standard testing instrument. The second is a switchboard instrument of the moving-coil pattern, while the third is of the moving-iron type. Those showing the worst results are large sector or edgewise instruments, and the last two are hardly sufficiently damped to be considered satisfactory, being given merely as examples.

Damping devices usually depend on one of three things :—

(1) Electrical eddy-currents.

(2) Fluid friction.

(3) Air friction.

In **moving-coil** permanent magnet instruments (p. 71) it is only necessary to construct the frame which carries the winding, of copper or aluminium, in order to render instruments with moderately short pointers quite dead-beat. With large sector and edgewise instruments, however, the damping is often less satisfactory. The disc or drum of **induction**

instruments (pp. 81 and 110) again affords a ready means of damping by the use of a permanent magnet. Eddy-current damping is also readily applicable to **electrostatic** and **hot-wire** instruments, but is less satisfactory with the **moving-iron and dynamometer** types, since, when these are used for direct current, the proximity of a strong permanent magnet considerably affects the readings, and although this can be allowed for in calibration, any weakening of the magnet with time will have its effect on the readings. With alternating currents also the field due to the winding gradually demagnetises the permanent magnet, unless it is carefully shielded, and the method is altogether inapplicable to instruments of these types, when intended for use on both direct and alternating current circuits.

The oldest method, and the one which is still commonly used where the moving parts are heavy (*e.g.*, multicellular electrostatic voltmeters) or where the working forces are great (*e.g.*, recorders) is **oil damping.** To be satisfactory the surface should remain continually immersed, as, if it is withdrawn from the liquid, a certain amount of oil will adhere to the surface, and "creeping" will result. If the axis of rotation is vertical a very efficient damper can be constructed on these lines, as shown in Fig. 10 (*c*) and also in Fig. 42. Provided the fine wire carrying the paddle is in line with the axis of rotation, no creeping is noticeable, and the possible damping is almost unlimited.

It was suggested by Dr. Frölich[1] many years ago, and subsequently by Mr. Holden, that the oil might be enclosed in a little capsule carried by the spindle, so that, instead of a paddle moving in oil, the oil would have to flow round inside the capsule. This ingenious device, however, is impracticable for most purposes owing to excessive "creeping."

[1] *Elek. Zeit.*, 1886, p. 197.

For commercial instruments, and particularly for portable patterns, the best damping device is, undoubtedly, that based on **air-friction.** One of the first **pneumatic dampers** was that of Evershed and Vignoles, shown at *a* in Fig. 10. The vane *v* swings in the double sector-shaped box which it fits with as little clearance as possible. At *b* is shown the damping piston first used by Messrs. Siemens & Halske. The piston passes along the curved cylinder, of round or rectangular section, without touching it at any point. There is not much to choose between these two systems; the former adds somewhat to the depth of the instrument, while the latter adds more weight; but this is of small importance since it can be so arranged as to counterbalance the weight of the pointer.

MEASUREMENT OF MEDIUM RESISTANCES.

Of the various methods which have been proposed for the measurement of resistance, undoubtedly the most generally used is that known as the **Wheatstone bridge.** A simple form of this, spoken of as the slide-wire bridge, is shown diagrammatically in Fig. 11. Here X is the resistance to be measured, R a known resistance (preferably of nearly the same value as X), and ab a fine wire stretched along a scale. The galvanometer G is joined up as shown, and can be connected to the slide-wire ab at any required point (c). On closing the battery key K, a current flows through acb and adb in parallel, and it can be shown that, if c is so chosen that the relation $\frac{ac}{cb} = \frac{R}{X}$ is fulfilled, then the points c and d will be at the same potential, and consequently, no current will flow through the galvanometer on closing the circuit. The procedure is therefore to slide the contact c up and down the wire ab until balance is obtained; that is to say, until closing

the galvanometer circuit produces no deflection, and then $X = R\frac{cb}{ac}$.

In order to save calculation, the slide-wire scale can be so graduated that the value $\frac{cb}{ac}$ is read off direct, in which case $X = R \times$ scale reading.

It can be shown that the relations given above hold good equally if the battery and galvanometer are interchanged,

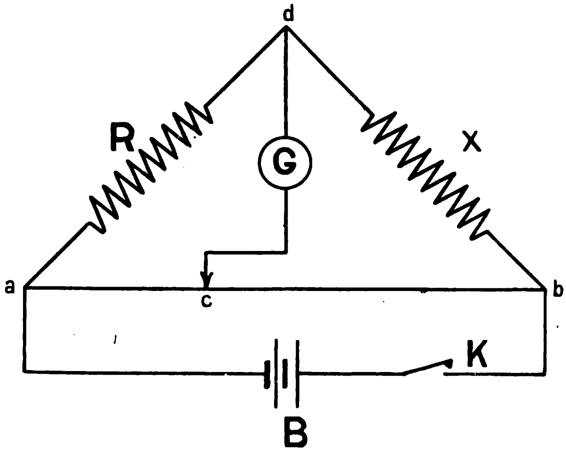


FIG. 11.—Slide-wire Wheatstone bridge.

that is to say, if the galvanometer is joined between the points *a* and *b*, and the battery between *c* and *d*. This arrangement, however, has the disadvantage that an appreciable current flows through the contact-maker, whereas in the other case, when a balance is obtained, no current flows.

The sensitiveness and accuracy of the method is greatest when R, X, ac and cb are all nearly equal, so that if R is adjustable it should be varied until the point of balance is nearly in the centre of the slide-wire. If the resistance X is high it is clearly impossible, with the ordinary stretched wire, to make $ac + cb = R + X$, but a special slide-wire, having

any resistance up to 10,000 ohms, has been introduced by Messrs. Everett, Edgcumbe & Co. It is made by winding a continuous spiral of wire, evenly spaced, on to a flat card some 12 in. long by 4 in. wide, which is subsequently bound round a circular drum, and held firmly in place. The galvanometer contact (c) is carried by an arm pivoted concentrically with the drum, and actuated by a milled knob. The knob also carries a pointer moving over a direct reading scale, and shows by its position at what point along the wire contact is being made.

The "**Everight**" **portable ohmmeter** embodies this construction, and the internal connections are shown in Fig. 12. The slide-wire itself only forms the central portion of the arms *ac* and *cb*, the remainder of the resistance (r_1 and r_2) being wound on bobbins inside the case. The scale, which is 12 in. long, is graduated from 10 to 110, and, by means of a multiple-way switch (R), any resistance from $\frac{1}{10}$ of an ohm to 11,000 ohms can be measured. When resistances higher than this have to be dealt with, the instrument is somewhat modified (see p. 47). The galvanometer, which is of the pivoted D'Arsonval type (see p. 57), is contained in the same case, and is so arranged that the weight of the coil is almost supported by a spring, so that friction is minimised.

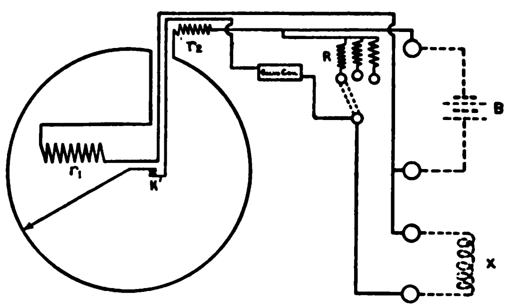


FIG. 12.—Connections of "Everight" ohmmeter.

When greater accuracy is required than is possible with the slide-wire bridge (say to within less than ½ per cent.) the three arms of the bridge may take the form of resistance coils, either in separate boxes or all fitted into one case. The most

usual form of bridge is that known as the **Post Office pattern.** The scheme of connections is shown in Fig. 13, the lettering being the same as in Fig. 11, so that the two can be at once compared. The resistances can be varied by short circuiting more or less of the coils by means of conical plugs, fitting accurately between blocks, to which the ends of the various resistance coils are soldered. *ac* and *cb* are known as ratio-arms, and usually consist of three coils each (1,000, 100, and 10 ohms respectively), giving ratios of 100:1, 10:1, and 1:1 as required. The arm *R* has, as a rule, a total resistance of more than 11,000 ohms, so that measurements up to 11,000 × 100 = 1,100,000 ohms can be made.

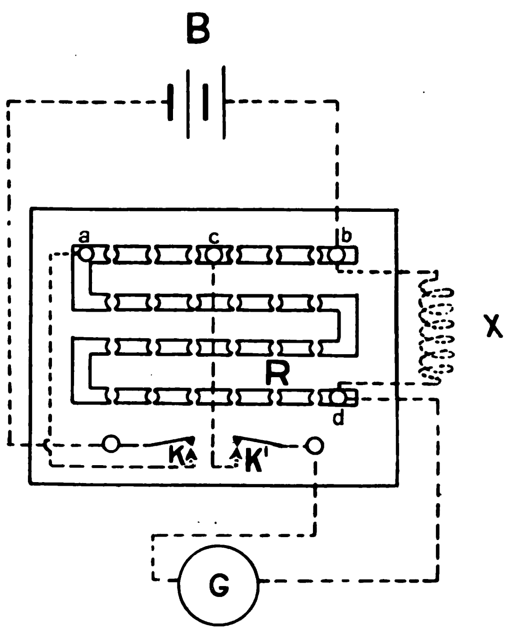


FIG. 13.—Wheatstone bridge, Post Office pattern.

In another form of bridge, known as the **dial pattern,** the resistance arm *R* consists of from three to six dials, each having 10 coils, more or less of which can be put in circuit by means of a plug. The value of each of the coils in a dial is the same, being, say, 1, 10, 100, and 1,000 ohms respectively. This form is somewhat more convenient to use and check, but is considerably more bulky and expensive.

To avoid the inconvenience of having loose plugs, some

bridges are made with switch contacts, which, while being extremely handy, require great care, both in construction and maintenance, if contact errors are to be avoided.

The contacts, plugs, etc. of all bridges and resistance boxes should occasionally be cleaned with a soft cloth dipped in paraffin. The tops of such boxes being usually of ebonite, care must be taken not to leave the plugs pressed tightly home when the bridge is out of use, or the ebonite may become permanently distorted, owing to the strain thereby thrown upon it.

Unless special precautions are taken, the Wheatstone bridge is not a suitable instrument for the measurement of resistances of much less than one-tenth of an ohm, owing chiefly to the difficulty of avoiding contact errors both in the bridge itself and in the wires which are employed to connect up the resistance to be measured (see p. 52).

MEASUREMENT OF HIGH RESISTANCES OR INSULATION.

The measurement of high resistances is usually carried out by one of **three methods**:—

(1) Direct deflection.

(2) Wheatstone bridge.

(3) Loss of charge.

Of these, the **direct deflection** is the most universally applicable, and consists in sending a current through the resistance to be measured in series with a galvanometer, and noting the deflection. The connections are shown in Fig. 14, where a cable test is taken as an example. The core of the cable is joined to one terminal of a sensitive galvanometer, the other terminal of which is, in its turn, connected to one pole of a battery, the other pole of which is earthed. On closing the key K, a current flows in series through the

insulation to be measured and the galvanometer, producing a deflection d_1. If now a known resistance, R, is substituted for the cable, and a second deflection, d_2, obtained, then, assuming the deflections to be proportional to the currents flowing through the galvanometer, the insulation resistance of the cable will be $R \times \frac{d_2}{d_1}$.

It is here assumed that the resistance of the galvanometer and battery are negligibly small, compared both with that of the resistance R, and of the insulation under test. If this is not the case, allowance must be made for their resistance. If proportionality between deflection and current cannot be relied upon, d_1 and d_2 should be made approximately equal, either by shunting the galvanometer, or by varying the voltage of the battery, due allowance being made for this when calculating the insulation.

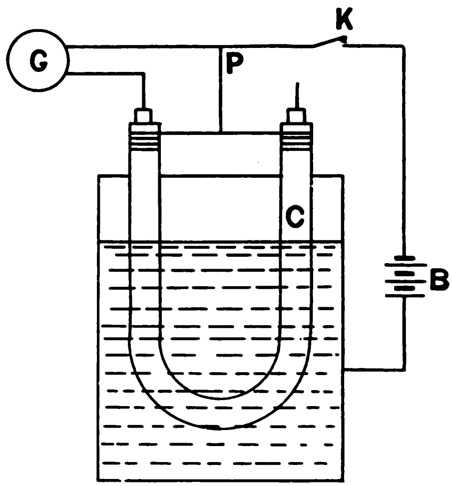


FIG. 14.—Measurement of insulation by direct deflection method.

It will be at once seen that there is a great chance of **surface leakage** over the ends of the cable, and that, in fact, this leakage might be much greater than that taking place through the insulation itself. The error can, however, be easily eliminated by the use of what is known as "Price's Guard Wire" shown at P. It consists of a length of bare copper wire twisted round the insulation between the core and the

sheath or "earth." It will be seen from Fig. 14 that, with this arrangement, any current leaking over the surface of the cable ends will flow through the wire P and not through the galvanometer, so that any inaccuracy due to surface leakage is eliminated.

A short-circuiting key or plug should be provided for the galvanometer, as, if the circuit C has capacity, a comparatively large current rush will take place on closing or opening the key K, and, even if it does not actually damage the galvanometer, it will very probably cause a change of zero, and should be avoided.

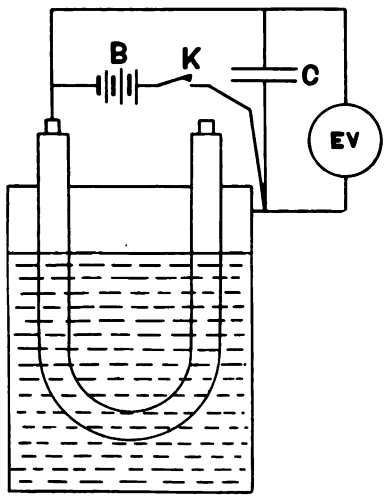


FIG. 15.—Measurement of insulation by loss of charge method.

The **Wheatstone bridge method** has been already described (p. 39); the only additional precautions to be taken in this case being to ensure that the insulation of the bridge and connections is good. As far as possible in this, as indeed in all insulation tests, the connecting wires should be stretched in mid-air and not allowed to rest on the table or ground. A guard-wire can be employed in this case also, its free end being connected to the other pole of the battery.

In the **loss of charge method** a condenser is connected across the terminals of the insulation to be measured, in parallel with an electrostatic voltmeter, as shown in Fig. 15. Let C represent the capacity of the condenser in microfarads, t the time taken in seconds for the potential difference at the terminals of the condenser (as shown by the voltmeter) to fall

from V to v, then the insulation resistance in megohms is $\dfrac{0{\cdot}4343\ t.}{C\left(\log \dfrac{V}{v}\right)}$.

If v be half V the insulation resistance is very approximately $1{\cdot}428\ \dfrac{t}{C}$.

In making the test, the key K is closed, and the deflection on the electrostatic voltmeter noted. K is then opened, and the deflection again observed after a time t.

It should be remarked that the utmost care is necessary as regards the insulation of the various instruments, particularly of the key K, as should there be an appreciable leak across this, the result would be entirely vitiated. Nor must it be assumed that the insulation of either the condenser or the voltmeter is perfect. The insulation resistance of the entire system, without the cable under test, should be first determined, as described above, a second reading being then taken with the cable also connected up. From these two readings the value of the insulation under test can be at once deduced, it being remembered that the resistances are in parallel. Thus, if the unknown resistance of the cable be R, that of the testing apparatus R_1, and the combined resistance R_2, then

$$\frac{1}{R} = \frac{1}{R_2} - \frac{1}{R_1}.$$

When comparing insulations the **following data should always be recorded,** as the value found for the insulation depends on them all: (a) Voltage applied; (b) Temperature of insulating material; (c) Duration of electrification; (d) Whether the positive or negative pole of the battery is to earth.

Whilst for the measurement of high insulations, say, above 500 megohms, the direct deflection and loss of charge methods are practically all that are available, it is of the utmost

importance for the engineer to be able to make such measurements as are met with in house installations, etc., with rapidity and fair accuracy, and without the comparatively complicated and delicate apparatus described above. For this purpose there are several **direct reading instruments** on the market, of which the best known are the Evershed, the Nalder, and the Everett-Edgcumbe.

The **Everett-Edgcumbe ohmmeter** is similar in construction to the resistance indicator described on p. 41 except that the resistance of the slide-wire is greater, and a higher resistance standard is used. A magneto-generator, giving usually 200 or 500 volts, is employed as the source of current, and the scale is direct reading. In external appearance it is similar to the resistance set previously described, and is identical with this as regards size. The standard ranges are 10,000 ohms to 50 or 200 megohms, and a combined set, having a range of $\frac{1}{10}$ ohm to 50 or 200 megohms, is made without increase of size.

The **Evershed set,** which has undergone considerable improvement since its first introduction, some 15 years ago, is based on what is often spoken of as the "ohmmeter" principle. Two forms are shown diagrammatically in Fig. 16. Assuming the battery (B) to give constant voltage, the force exerted on the needle (n) by the coil a will be constant, whereas that due to coil b will depend on the value of the resistance X. If the needle n is pivoted, and carries a pointer moving over a scale, this latter can be so graduated as to read direct in ohms. A little consideration will show, moreover, that the position taken up by the needle will be independent of the voltage of the battery, since any increase or decrease in this will affect both a and b equally.

The earlier Evershed ohmmeters were constructed on this principle, the only important modification being that the needle n was strengthened by being magnetised by a coil connected

in series with *a*. The disadvantages of such an instrume were that it was much affected by stray magnetic fields, a

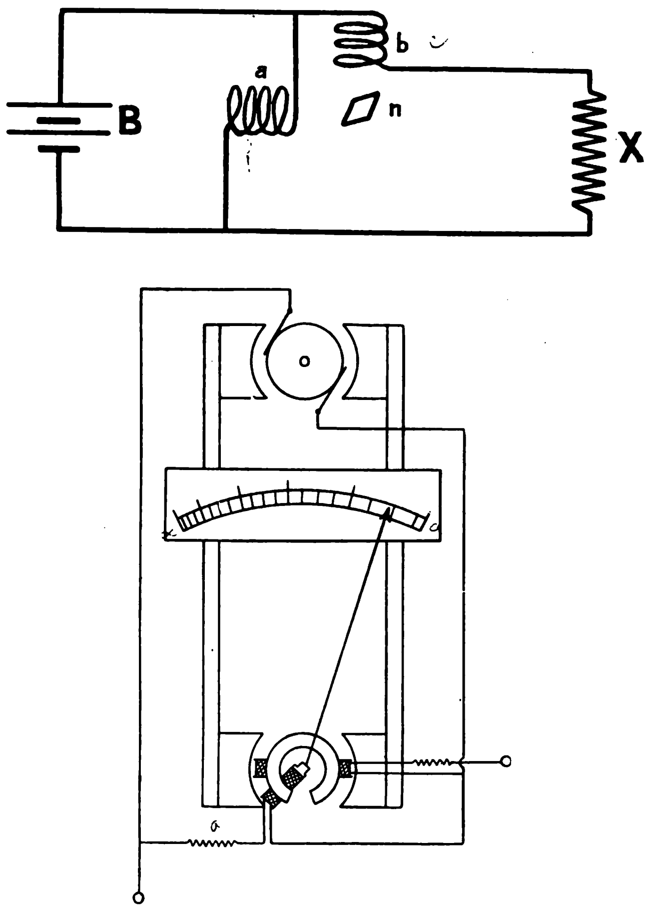


FIG. 16.—Principle of Evershed ohmmeter and "megger."

that the working forces were extremely small, while t weight of the moving magnet was necessarily considerable.

In the latest form, known as the "**Megger**" a differe

construction is adopted. Two coils, which may be called respectively the pressure coil and current coil are employed (corresponding to *a* and *b* in the upper Fig. 16) and moreover, instead of their being fixed, and the magnet pivoted, the coils are pivoted and the magnet fixed. The principle of action is shown diagrammatically in the lower Fig. 16, from which it will be seen that the current coil resembles that of an ordinary moving-coil instrument. The pressure coil; on the other hand, threads on to an annular core, so that, when the pointer is at "infinity" on the scale the pressure coil is in a very weak field, and experiences little or no torque; whereas when at zero, it is under the pole, and the field is comparatively strong. As a result, the moving system finds a stable position for every value of external resistance, from zero to "infinity," and moreover the scale is very open at the lower end and close at the upper; so that approximately the same percentage accuracy is possible throughout (see p. 8). As will be seen, the same magnetic system furnishes the field for both the meter and the generator, and since the pressure and the current coils both move in the same field, the readings are independent of the strength of the magnet. Current is led into and out of the moving-coils by means of three thin phosphor-bronze wire spirals, which exert a negligibly small torque on the moving system.

The principle of action of the Nalder ohmmeter, which is known as the "**Ohmer**" is shown diagrammatically in Fig. 17. It is constructed on the electrostatic principle, and in order to secure sufficient power, a number (13 in all) of vanes (*V*) are placed one above the other on the spindle, working in a corresponding number of cells *A* and *B*. In the actual instrument there are 4 sets of cells, those diametrically opposite being connected together, but only two are shown in Fig. 17, for the sake of clearness. In use the terminal *E* is connected to "earth," and terminal *L* to the circuit to be tested. On

turning the handle of the generator, which is contained i ohmmeter case, a difference of potential is established be *A* and *V*, and the pointer comes to rest at ∞, so lo the resistance between *E* and *L* is infinite. So soon, ever, as a circuit is established between them, owing fault in the insulation under test, a current will flow th the resistance *R*, and, as a consequence, the potentials

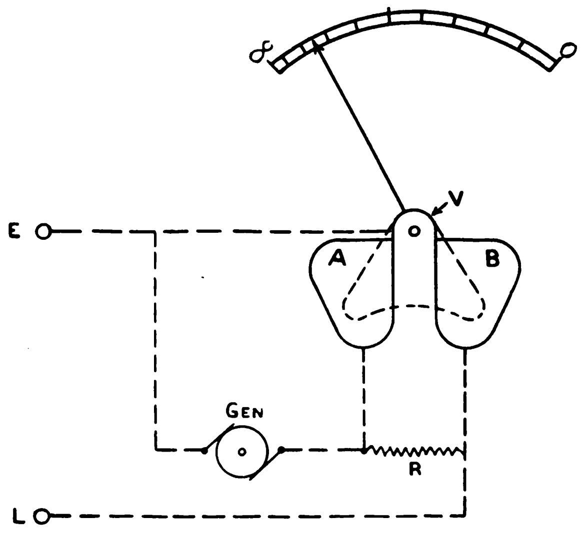


FIG. 17.—Nalder "ohmer."

and *B* will no longer be the same, owing to the drop in along *R*, and there will be reduced attraction between *V* a so that the former will take up a new position dependi the strength of the current flowing. It will be seen tha position is quite independent of the voltage of the gene as any variation in this will affect the potential differ between *V* and *A* or *B* equally.

For some special purposes it is found convenient to **op** **the Wheatstone bridge with alternating currents**

;, an induction coil (having usually a ratio of 1 : 1) is ed between the battery and the bridge, while a tele- eceiver replaces the galvanometer. By means of such gement the resistance of polarisable electrolytes can be measured. This device is often employed also, ure the resistance to earth of a system of lightning s, as owing to earth currents and electrolytic E.M.F.'s earth-plates ments made with current are very le. The alternat- phone method can oyed for all resist- easurements, but is rly so sensitive as ect current, nor is onvenient, owing to that the telephone o indication as to rection in which ent is required. An e cessation of buz- , moreover, never l.

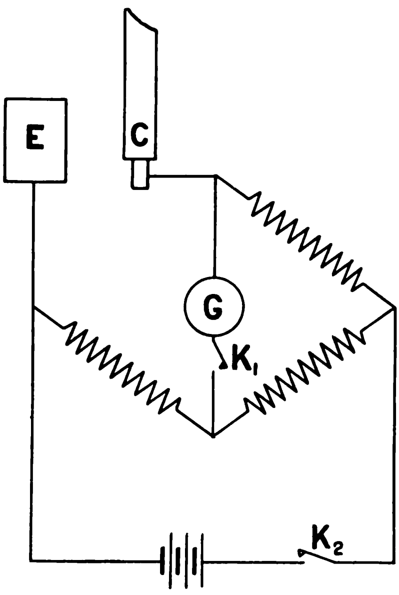


FIG. 18.—Measurement of network insulation with a Wheatstone bridge.

ould be noted that Wheatstone bridge e holds good even he **galvanometer has a permanent deflection,** an E.M.F. in one or more of the arms. The n of balance in this case is that the deflection s **unchanged** when the battery circuit is closed ned. Thus it is, for example, possible to determine ulation resistance of a network while working as shown 18.

MEASUREMENT OF LOW RESISTANCES.

Numerous methods for low resistance measurement have been suggested from time to time, such, for example, as the **Carey-Foster bridge,** the **Kelvin bridge,** and the **differential galvanometer,** but although capable of extreme refinement, they have not found much favour with engineers, owing, perhaps, chiefly to the special nature of the apparatus required.

When a **Wheatstone bridge** is to be employed for the measurement of such low resistances, the precaution should always be taken of first clamping together the outer ends of the two connecting wires and measuring their resistance, the value so obtained being subtracted from that found for the resistance under test.

For the measurement of resistances too low to be accurately dealt with by the Wheatstone bridge, the potentiometer is, as already pointed out, undoubtedly the most satisfactory instrument to employ, and owing to its general adaptability it may be well to describe it here as a whole, and not merely as applied to the measurement of resistance.

THE POTENTIOMETER.

The principle of the method will be gathered from Fig. 19. B_1 is a cell giving a fairly constant current, preferably an accumulator. Across its terminals is connected a stretched wire, the resistance of which is unimportant, so long as it is uniform throughout its length. If now another cell B_2, of lower E.M.F. than B_1, is connected, as shown, through a sensitive galvanometer G, on to the slide-wire, it is clear that a point on the latter can be found such that when contact is made the galvanometer shows no deflection. This will occur when the fall of potential along the wire from the point A is equal to the E.M.F. of B_2. If another cell B_3 is connected

up in place of B_2, and another point of balance found (the distances of these two points from the end of the slide-wire being a_2 and a_3 and the E.M.F. of the two cells V_2 and V_3 respectively), we have

$$\frac{V_2}{V_3}=\frac{a_2}{a_3}.$$

Hence, if the E.M.F. of V_2 is known, that of V_3 can be at once calculated.

Any increase in the potential difference between A and C will clearly increase the readings a_2 and a_3 in the same proportion, and *vice versâ*, so that it is easy to bring the point of

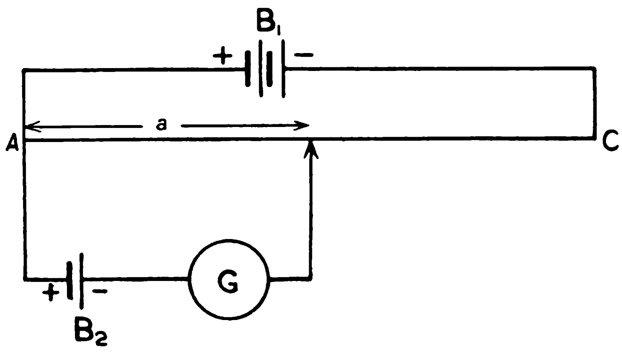


FIG. 19.—Connections of simple potentiometer.

balance to any required spot along AC. Suppose that the wire AC is stretched over a scale divided into 150 parts, and that the E.M.F. of B_2 is known to be 1·43 volts. Let the contact be set in such a position that a equals 143 divisions, the potential difference between A and C being so adjusted, by means of a resistance in the main circuit, that on closing the galvanometer key no deflection is observed. On substituting B_3 for B_2 a point of balance can be again found, for example, at the point 135, and it is then clear that the E.M.F. of B_3 is 1·35 volts. In this way the scale becomes direct reading, and any number of E.M.F.'s can be read off in rapid succession.

The practical development of this system has been due chiefly to Colonel **Crompton**, who many years ago introduced a number of improvements. In the first place, it will be noticed that the accuracy of reading depends on the slide-wire being of considerable length (say, not less than 5 ft.), and it must, at the same time, be perfectly uniform in section, in order that the resistance per unit length may be constant. It is, however, by no means necessary that the entire length should be stretched over the scale, and in Colonel Crompton's potentiometer $\frac{14}{15}$ of the slide-wire is wound on bobbins inside the case of the instrument. The actual slide-wire is 105 centimetres long, and is divided into 1,050 equal parts.

Fig. 20 shows the connections in diagrammatic form. The

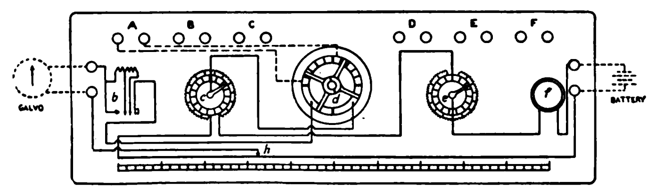


FIG. 20.—Crompton potentiometer.

pairs of terminals *A*, *B*, *C*, *D*, *E* and *F* are connected to the various stops of the double-pole six-way switch *d*. In the diagram, in order to avoid confusion, only the terminal *A* is shown so connected. The 14 coils, each of exactly the same resistance as the slide-wire, are joined to the switch studs *c*, and current from a 2-volt accumulator is passed through the slide-wire, in series with these coils, the adjustable resistance *e*, and the fine adjusting rheostat *f*. The studs *c* are numbered 0 to 14. Supposing, now, that the switch arm is set on stud 12, and that the slider makes contact with the slide-wire at the point marked 76 (the maximum scale reading being 100), the galvanometer circuit then bridges over a resistance equivalent to a reading of 1,276 on the slide-wire.

The E.M.F. of a Clark cell, which forms the usual standard of voltage, is 1·433 volts at 15° C. (see p. 56). Let the switch arm *c* be placed at 14 with the contact *h* at 33, and the rheostats *e* and *f* be adjusted until a balance is obtained with a Clark cell connected to one pair of terminals, the switch *d* being so set as to connect that pair in circuit with the galvanometer. When so arranged, the instrument becomes absolutely direct-reading. For example, the reading assumed above represents 1·276 volts, and so forth. A number of different cells can be connected to the various terminals *B*, *C*, *D*, etc., and their E.M.F.'s read off in succession.

For the measurement of **voltages** higher than 1·5, which, as will be seen, is the maximum which can be read off direct, ratio resistances are employed. For example, if it is required to measure potential differences up to 150 volts, a resistance box could be employed having three terminals, T_1, T_2, and T_3, such that the resistance between T_1 and T_3 was 100 times that between T_1 and T_2. Then if terminals T_1 and T_3 be connected to the circuit to be tested, and T_1 and T_2 to the potentiometer, it is merely necessary to multiply the potentiometer reading by 100 to obtain the potential difference required.

The potentiometer method is not restricted to the measurement of voltage, since, owing to the fact that the potential difference at the terminals of a resistance is directly proportional to the **current** flowing through it, it is merely necessary to pass a current, the value of which it is to be determined, through a known resistance R, and to measure the resulting potential difference at its terminals. Then if R be a round number of ohms (for example, 0·001, 0·1, 10, etc.) the potentiometer becomes direct reading in amperes, it being merely necessary to move the decimal place. For the construction of such standard resistances, or shunts as they are often called, see pp. 24, and 75.

Finally, by connecting a known **resistance** in series with an unknown, and comparing the potential differences at the terminals of each, when the current is passed through both in series, the value of the unknown resistance can be at once determined.

A great advantage possessed by the potentiometer method of measurement, apart from its universal applicability, is the fact that no current actually flows through the wires connecting the instrument with the circuit to be measured. Besides very much simplifying the connections, all contact errors, etc. are thereby eliminated.

As the source of current, a 2-volt accumulator should be employed, since a steady current is essential. A galvanometer of the D'Arsonval pattern (p. 57) will be found the most convenient as being dead-beat. In Fig. 20 at *b* a successive contact key is shown, whereby resistance is successively cut out of the galvanometer circuit, as a balance is more and more nearly attained. This arrangement is much to be preferred to the alternative of shunting the galvanometer, as the latter device allows a fairly large current to flow, which may be detrimental to some part of the apparatus, particularly the standard cell.

As regards a **standard cell,** the choice lies between :—

(1) The Board of Trade **Clark** cell (mercury/mercurous sulphate/zinc sulphate/zinc) whose E.M.F. at 15° C. is 1,433, and falls approximately 0·0012 of a volt, or 0·083 per cent. for each degree centigrade rise of temperature.

(2) The **Carhart-Clark** cell, the E.M.F. of which is the same as the Board of Trade pattern, but falls only 0·038 per cent. per degree rise of temperature. This cell, moreover, takes up the surrounding temperature more rapidly than does the Board of Trade form.

(3) The **Weston or Cadmium** cell. In this, cadmium takes the place of zinc, and the E.M.F. is 1·0188 volts at

15° C. and shows a decrease of only 0·00005 volts per degree rise of temperature.

Dr. Hibbert has also suggested a mercury/mercury-chloride/zinc-chloride/zinc cell giving an E.M.F. of 1 volt with a fall of 0·01 per cent. per degree centigrade rise, but, up to the present, the Clark and Weston cells have held their own.

GALVANOMETERS.

All bridge and potentiometer methods depend for their accuracy on the employment of a sensitive **galvanometer.** For portable use, or for rough work, a galvanometer carrying a pointer moving over a scale is all that is required, but for great accuracy a reflecting instrument should be used. An extremely sensitive instrument carrying a pointer is that constructed by **Paul,** who, by the use of a circular coil pivoted near its centre, obviates the necessity for accurate levelling. This instrument is of the D'Arsonval pattern, and it may be said that almost all galvanometers used in commercial work, whether of the pointer or reflecting type, are **D'Arsonval instruments.**

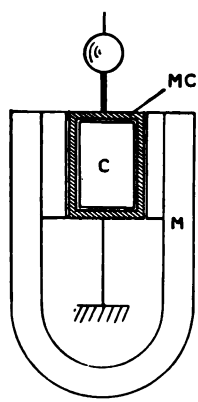


FIG. 21.—D'Arsonval galvanometer.

A typical galvanometer of this pattern is shown in Fig. 21. It consists, essentially, of a permanent magnet M, in the field of which is delicately suspended, or pivoted, the moving-coil MC, in such a way as to be capable of rotating about its axis in the comparatively narrow air-gap between the pole-pieces and the core C. To the coil is attached either a mirror, as in Fig. 21, or a pointer, according to circumstances.

The coil is usually controlled by the action of one or more

springs,[1] which also serve to lead the current into and out of the winding. They may take one of three forms: (1) A spiral; (2) A straight or twisted ligament supporting the coil, either from above only, or from above and below, as shown in Fig. 21; (3) A bifilar suspension consisting of two parallel supporting ligaments. A current flowing through the coil causes it to deflect to one side or the other round its axis, the motion being opposed by the tension of the spring.

In Wheatstone bridge work, as in fact with all null or **zero methods** as they are called, it is important that the sensibility of the galvanometer should be as great as possible at the

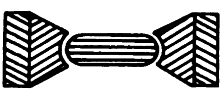


FIG. 22.—Pole-pieces for zero pattern D'Arsonval galvanometer.

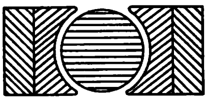


FIG. 23.—Pole-pieces for proportional scale D'Arsonval galvanometer.

point of rest, whereas it is of little importance what it may be elsewhere. With this end in view, the poles of the magnet are often shaped as shown in Fig. 22, whereby a very intense field is obtained at one point. For many purposes, however, as will be seen later, it is essential that the field should be as **uniform as possible** for all positions of the coil, and to ensure this, the poles and core are, as a rule, shaped as shown in Fig. 23.

The **sensitiveness** of the galvanometer depends, other things being equal, on the density of the magnetic field, and on the number of turns of wire in the coil, and various devices

[1] See also p. 15.

are in use whereby the coils can be readily interchanged, according to the sensibility required.

MEASUREMENT OF CURRENT.

For the *absolute* determination of current strength, the **electrolytic method** is by far the most satisfactory; and, for many purposes, such as the checking of dynamometers or balances, the copper voltameter deserves more attention than it, in general, receives, the operation being usually supposed to be more laborious and difficult than is actually the case. Provided a steady current can be maintained through the cell for, say, two hours, an accuracy of measurement to within ¼ per cent. can readily be attained.

A glass jar, some 10 or 12 in. high, by 6 or 8 in. in diameter, forms a suitable bath, and in this are hung the anode and cathode (*i.e.*, the plates leading the current into and out of the bath respectively). It is best to employ two anode plates, one hung on each side of the cathode on which copper is to be deposited. The exposed cathode surface should, in any case, exceed 30 sq. cm. per ampere, 50 sq. cm. per ampere being a very suitable value. The electrolyte consists of a nearly saturated solution of pure recrystallised copper sulphate in distilled water, having a density of from 1·1 to 1·2 (from 1·16 to 1·17 being found to give the best results). To this 1 per cent. by volume of pure sulphuric acid is added. The plates must first be cleaned in strong nitric acid, then washed in distilled water, and after thorough drying the cathode plate, or plates, must be carefully weighed. It is most important that after being cleaned they should not be again touched with the hand.

When the cathode has been dropped into its place in the solution, the current should be at once switched on, and kept absolutely constant throughout the test. After say two

hours (the time t in seconds having been carefully noted) the circuit is broken and the cathode washed, dried, and again weighed. The current in amperes is[1]

$$\frac{\text{gain in weight of cathode in grammes}}{t \times \cdot 0003286}.$$

As will be seen, the electrolytic method is slow, and does not admit of extreme accuracy. For this reason the **potentiometer arrangement** (see p. 52) is to be preferred, so far as direct current measurements are concerned, while the **Kelvin balance or Siemens dynamometer** are available for alternating currents.

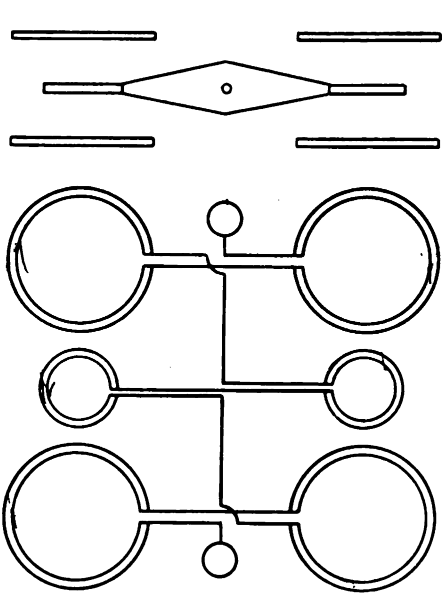


FIG. 24.—Diagram of Kelvin balance.

The **Kelvin balance** consists of two coils fixed one at each end of a swinging beam, which allows them to oscillate between two other pairs of coils as shown in Fig. 24. The current to be measured is passed through the six coils in series, being led into the pair of moving coils by means of thin copper ligaments. As a result of the interaction of the magnetic fields, the left-hand end is depressed, and the right-hand end elevated. This motion is opposed by a weight which can be slid along the graduated beam from one end to the other.

[1] A. W. Meikle, *Proc. Phys. Soc. Glasgow Univ.*, 1888.

The beam carries an index pointer, and, when no current is passing, an adjustable counterweight is so set, that with the sliding weight at the zero point of the scale, the beam is balanced and the index stands opposite a fixed mark. Upon passing a current through the system, balance is destroyed, and is restored by sliding the weight along the beam. Since the torque exerted on the coil is proportional to the square of the current, the amperes flowing will be proportional to the square root of the distance through which the weight has to be displaced, in order to restore equilibrium.

These balances are made for various ranges, and each has four sliding weights with their corresponding counterweights, so that an extended range is obtained. Besides being used as ammeters they are also made in the form of voltmeters and wattmeters. In the latter case the current passes through the fixed coils, while the moving system carries the volt-coils, so that the watts are directly proportional to the displacement of the weight.

As will be seen from Fig. 24 the system is perfectly astatic, a stray magnetic field merely attracting or repelling the moving system as a whole, and exerting no turning moment upon it. These balances are practically useless for a rapidly varying current, as the moving system begins to oscillate and cannot be brought to rest. As ammeters or voltmeters they are equally accurate, whether used for direct or alternating currents, and are permanent in their calibration. They can, moreover, be checked with direct current, and subsequently used for alternating current measurements.

Another instrument which is extensively used as a sub-standard, especially for alternating currents, is the **Siemens dynamometer.** The principle of action is shown diagrammatically in Fig. 25, the instrument being wound as an ammeter. The coil A is suspended from above by a silk thread, and has its magnetic axis perpendicular to that of the

fixed coil (*B*). Current is passed through the two coils in series, being led into *A* by means of the mercury cups *CC*, arranged, as shown, one above the other, so as to reduce friction to a minimum.

The coil *A* thus finds itself in a strong magnetic field, due to *B*, and tends to rotate about a vertical axis. The motion is opposed by the spring *D* attached to the milled knob *E*, which is turned until the pointer *F* shows that the moving coil has been restored to its normal position at right angles to the fixed coil. Since the force exerted by the spring is proportional to the angle of torsion, it follows that the angle through which the knob *E* has to be turned, as shown by the pointer *G*, is a measure of the force exerted on the coil *A*, which is, in its turn, proportional to the square of the current. Hence it follows that the current is proportional to the square root of the angle through which *E* has been turned.

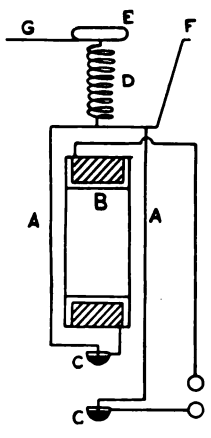


FIG. 25.—Siemens dynamometer.

The coil *A* usually consists of one turn only, while *B* has a number of turns, and is often provided with two distinct windings, so as to increase the range by giving two sensibilities. Besides the incidental advantage of lightening the moving system, it is always advisable to have as few turns on *A* and as many on *B* as possible, since the torque exerted depends on the product of the two; whereas the disturbance due to stray magnetic fields is directly proportional to the number of turns on *A*. This is equivalent to saying that the fixed field should be as strong as possible. In order to eliminate altogether this very serious source of error, the whole may be rendered astatic, by mounting two complete systems on one spindle, so connected that any external field

will urge one moving coil in one direction, and the other in the opposite direction, whereby the disturbing forces cancel out.

The dynamometer, like the Kelvin balance, can be constructed either as an ammeter, a voltmeter, or a wattmeter. In the latter case the moving system usually forms the pressure circuit. It shares with the balance the advantage of being equally accurate whether used with direct or alternating currents (see p. 64), so that it can be adjusted or checked on direct current, and subsequently employed to calibrate alternating current instruments. Dynamometers, however, labour under the great disadvantage that, unless astatically wound, they are very seriously disturbed by stray magnetic fields, including that of the earth, and further the mercury cups give a considerable amount of trouble.

Deflectional dynamometer ammeters and voltmeters, constructed on the same lines as the wattmeter described on p. 99, have found a limited use, chiefly for laboratory work. The scales are, as a rule, far from evenly divided, since they follow a square law, and, in the case of ammeters, owing to the fact that only a small current can conveniently be led through the moving coil, the drop is usually high.

MEASUREMENT OF POTENTIAL.

Any of the current measuring instruments, just described, can be used to measure differences of potential, so long as the resistance of the instrument itself remains constant. Since by Ohm's law $E = C \times R$; if R (the resistance of the instrument) is known, and C is measured, then the difference of potential (E), at the instrument terminals, can be calculated, or as is more usual, the scale can be graduated in volts instead of amperes.

Only two instruments are in use which **measure potential**

directly, the potentiometer (see p. 52) and the electrostatic voltmeter (see p. 84), all others being based on the indirect method. The various precautions which have to be taken when using these will be found under their respective headings.

MOVING-IRON AMMETERS AND VOLTMETERS.

These instruments, which are often loosely spoken of as "electromagnetic," "soft-iron" or even "gravity" pattern, may be divided into two main groups:—

(1) Those having only one iron, which is drawn into a coil under the influence of the current to be measured.

(2) Those in which the moving-iron is attracted or repelled by one or more fixed irons.

Before describing particular instruments, it may be well briefly to consider their **working in a general way,** more particularly as it is a subject which has not received very much attention. Taking the simplest case of two pieces of soft iron inside a solenoid, one of them fixed, and the other attached by an arm to the spindle carrying the pointer; it is clear that these two pieces of soft iron will repel one another, with a force proportional to the product of their respective magnetic fields. If the permeability of the iron can be regarded as constant throughout the range of the instrument, the field due to each will be proportional to the current flowing, so that the torque at every point will be **proportional** to the **square of the current.** This is a most important condition, since, on the completeness with which it is fulfilled depends the suitability of the instrument for use with alternating current. Since the effective value[1] of an alternating current is represented by the square root of the average square of the instantaneous values,

[1] An alternating current, having an "effective" (or R.M.S.) value of A amperes, has the same heating effect as a continuous current of A amperes.

thermo-junction (J). The heating coil ($H.C.$) consists of a platinum spiral, wound non-inductively, or, when extremely low currents are to be measured, of a platinised quartz thread. It is possible, with a galvanometer constructed on this principle, to measure currents as small as a tenth of a milliampere, and it can be used indiscriminately for direct or alternating current of any frequency, so that it should form a very valuable instrument for many purposes where extreme accuracy is not required.

INDUCTION OR FERRARIS AMMETERS AND VOLTMETERS.

It is curious that **Ferraris,** to whose researches the induction motor is so largely due, thought, at first, that its efficiency must necessarily be so low as to make it impracticable, and therefore devoted his attention primarily to induction measuring instruments. It is, however, only within the last few years that they have been brought to any degree of perfection. They may be divided into two classes:

(1) Shielded pole type.

(2) Split circuit type.

The **shielded pole pattern** is the simplest, and is shown in Fig. 39. The aluminium disc A, which is pivoted in jewels, passes between the poles of the electro-magnet B energised by the current to be measured. C and E are copper plates, which cover about three-quarters of the magnet poles, and project slightly beyond them. When a current is sent through the coil, part of the flux passes through the disc direct, and part through the copper shields CE. Eddy-currents are thereby induced in both disc and shields, and, flowing as they do, in the same sense, they attract one another. The disc, therefore, experiences a turning moment in the direction shown by the arrow. The torque is proportional, at any given frequency, to the product of the current induced in the disc,

into that induced in the shields, that is to say, to the square of the magnetic flux, which is, in its turn, roughly proportional to the current in the coil *D*. The motion is usually opposed by a spiral spring, so that the angle turned through is approximately proportional to the square of the current. The disc carries a pointer travelling over a scale graduated in amperes or volts, as the case may be, and the movement of the disc is damped by means of a permanent magnet.

The scale so obtained has the disadvantage common to all "square law" instruments, of being close at the beginning and excessively open at the end. This can be overcome in two ways. A **cam-shaped disc** can be used, so that, as it

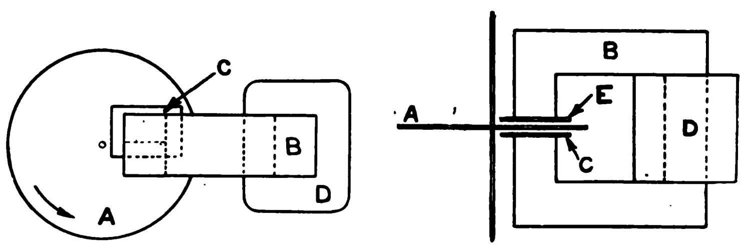


FIG. 39.—Shielded-pole induction ammeter.

rotates, less and less of it lies between the poles of the electromagnet. By properly shaping the disc a scale of 300° can be obtained, practically even above the first 10 per cent. Messrs. **Siemens & Halske** attain the same end, over a 90° scale, by employing an auxiliary weight, which, when the pointer is at zero, is urging the disc forward, in opposition to the spring, while at the end of the scale it is vertically below the spindle.

It must be remembered that the currents, both in the disc and shields, are proportional to the frequency, neglecting the reaction of the eddy currents on the field strength, so that, unless some precautions are taken, the indications will be

extremely sensitive to **changes of frequency.** In the case of voltmeters, however, partial compensation is possible by making the circuit inductive, since the flux for any given impressed voltage will then be inversely proportional to the frequency, and the strength of the induced currents (which are proportional to frequency × flux) will be but slightly affected. In the case of ammeters, on the other hand, the problem is less simple. The usual arrangement is to shunt the magnet winding by a non-inductive resistance, which, as the frequency rises, carries a larger and larger proportion of the total current.

Both these methods of compensation have, however, the disadvantage that the **temperature error** of the instrument is increased, owing to the fact that the magnet windings must of necessity consist of copper. The temperature coefficient is already high, since the induced currents are inversely proportional to the specific resistance of the disc and shield, which are of copper or aluminium. A compromise is thus necessary, and it is, in practice, difficult to reduce the temperature error below 0·1 per cent. per degree centigrade in voltmeters and 0·2 per cent. in ammeters. The respective frequency errors would average say 4 per cent., for a charge of frequency from 40 to 60 cycles per second, in the case of a voltmeter, and 10 per cent. for an ammeter.

In common with all other instruments which obey the square law, induction instruments are practically independent of the wave-form of the current or voltage (see p. 65).

Split-phase induction ammeters and voltmeters are constructed on similar lines to the wattmeters described on p. 110, the phase being split by making one circuit non-inductive, and the other highly inductive. Whilst in the case of wattmeters it is of the utmost importance that the two fluxes should be precisely 90° out of phase (see p. 113), with ammeters and voltmeters, on the other hand, this is quite

immaterial, so that no elaborate phase-splitting devices are necessary.

ELECTROSTATIC VOLTMETERS.

In these instruments the voltage is measured by the attraction or repulsion of two electrified bodies. A simple form of such an instrument is shown in Fig. 40. Assuming the segments A and B to be oppositely electrified (*i.e.* connected to opposite poles), and the pivoted needle or vane (N) to be connected to the same pole as B, then N and B will repel, while N and A will attract one another. As a result, the needle will be deflected with a force depending upon the respective electrifications.

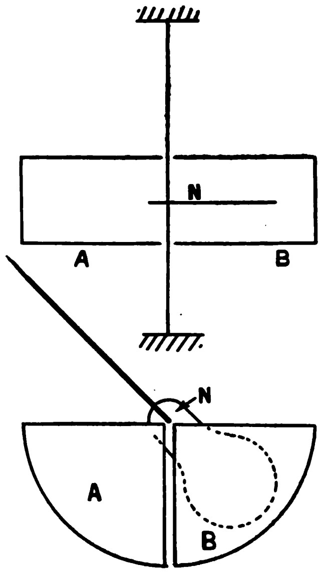


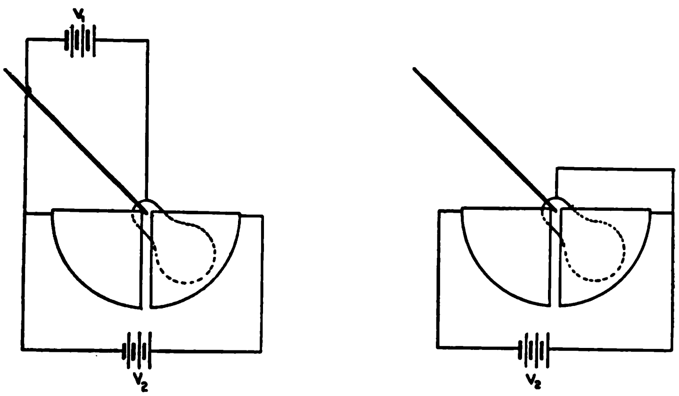
FIG. 40.—Simple electrostatic voltmeter.

In order to use such an instrument as a voltmeter, two courses are open, as shown in Fig. 41. (1) the pressure to be measured (V_2) can be applied between the two segments, and a known pressure (V_1) between the needle and one of the segments. The torque in this case, which is known as the **heterostatic** arrangement, is proportional to $V_2\left(V_1 - \frac{V_2}{2}\right)$. (2) With the **idiostatic or homostatic** arrangement, no auxiliary pressure is required. That to be measured (V_2) is connected, as before, between two of the segments, while the needle is joined up to one of them. The force is now proportional to $(V_2)^2$.

This latter arrangement is the one almost always employed

for alternating current measurements, and, since the torque is proportional to the square of the pressure, it follows that the indications of an electrostatic instrument are independent of both frequency and wave-form.

Perhaps the greatest difficulty to be contended with, in the design of a satisfactory electrostatic voltmeter, is the smallness of the working forces, particularly in the case of low voltage



Heterostatic connection of electrostatic voltmeter. Idiostatic connection of electrostatic voltmeter.

FIG. 41.

instruments. With a view to increasing the torque: (1) The distance between fixed and moving plates is reduced to a minimum, and the following table will serve as a guide in this respect:—

Pressure.	Sparking distance between point and plane.[1]	Suitable minimum gap between vanes.
2,000	0·02 inch	0·2 inch.
4,000	0·05 ,,	0·35 ,,
6,000	0·10 ,,	0·5 ,,
10,000	0·23 ,,	1·0 ,,
15,000	0·42 ,,	1·5 ,,
20,000	0·58 ,,	2·0 ,,

[1] See *Elektrotechnische Zeitschrift*, 1904, p. 841.

(2) The moving vane may be made double ended, as indicated in Fig. 42.

(3) The number of fixed and moving vanes can be increased, as in the multicellular construction due to **Kelvin,** and embodied in the instrument shown in Fig. 42, which shows one of the latest forms of multicellular electrostatic voltmeters, that due to **Hamilton.**

Unfortunately, however, both these devices increase the weight of the moving system, and, with it, the friction and want of dead-beatness. It was suggested by **Holt** some years

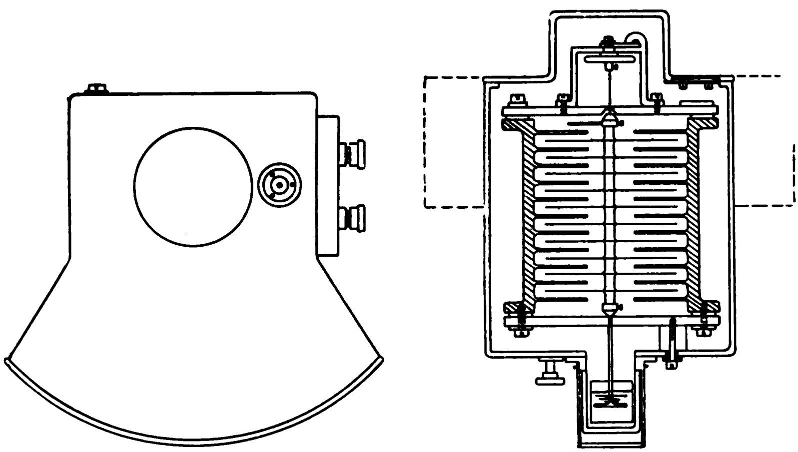


FIG. 42.—Multicellular voltmeter, Hamilton pattern.

ago that the weight of a vane might be considerably reduced, without materially interfering with its effective surface area, by cutting a number of small holes in it, and that, by the same means, the shape of the scale could be varied. This suggestion has been followed in some cases, but it will usually be found that the strength of the vane is thereby so far reduced that it is preferable to employ one of thinner material, and to omit the holes.

In many instruments an oil damping arrangement is employed, consisting either of a vertical paddle, or of a disc lying horizontally in oil as described on p. 39, and indicated in Fig. 42. For the reasons there given, however, most makers of high-tension electrostatic voltmeters have now abandoned oil for either magnetic or pneumatic damping.

In view of the smallness of the available working forces, and the very considerable weight of the moving system, extreme care must be devoted to the **pivoting** of the needle. It has been found that, in most cases, the ordinary pivots and jewels introduce too much friction (particularly with a horizontal spindle) to be satisfactory in the long run. Swinburne at one time employed a system of friction wheels, but a much better arrangement is that shown in Fig. 5, consisting of two steel points resting in polished steel cups.

Owing to surge effects in cables (see p. 200), particularly when switched into circuit, high-tension voltmeters are liable to be subjected to **sudden rises of pressure** enormously above their normal range. Precautions have therefore to be taken to prevent sparking across inside the instrument, when such surgings occur. To this end the air spaces should all be as large as possible; but that between the fixed and moving vanes is limited, as has been seen, by the weakening of the working forces. The dielectric strength is sometimes increased, either by the introduction of a sheet of mica,[1] or by covering the fixed vanes with a coating of insulating varnish, or varnished paper.

Whatever precautions are taken, however, as regards the instrument itself, some form of external protecting device is advisable. This usually takes one of these forms:—(1) a spark gap; (2) a fuse; (3) a high resistance. The first of these, which consists of an auxiliary **spark gap,**

[1] The breaking-down strength of mica may be taken as from 5 times (in thick sheets) to 150 times (in thin sheets) that of air.

shorter than any inside the instrument, must be regarded as bad practice, except for low voltage instruments, as it forms a weak spot on an installation probably otherwise very highly insulated and, should a spark at any time pass across, an arc is very liable to follow.

A **fuse** suffers from much the same disadvantage, except that the gap between poles, should the fuse melt, can be made considerably larger, but the current which the fuse will carry, momentarily, is quite sufficient to do considerable damage to the instrument.

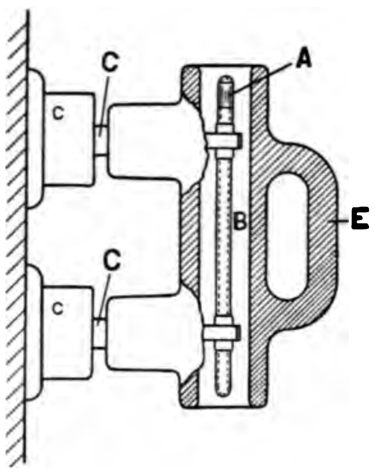


FIG. 43.—Ferranti water fuse for electrostatic voltmeters.

It may safely be said that neither of these devices should be employed, unless in combination with a high **resistance** which latter in itself affords complete protection. A resistance varying from $\frac{1}{2}$ to 10 megohms, according to the normal voltage, can be connected in series with each pole of the voltmeter without appreciably affecting the readings, the capacity current flowing into, and out of, the instrument being extremely small. Should a rise of voltage occur, sufficient to cause sparking between the vane and quadrant, the increased current automatically lowers the voltage, so that an arc is impossible.

The resistance may be fitted inside the instrument itself, or preferably in an accessible position where, incidentally, they may form a means of cutting the voltmeter out of circuit. Fig. 43 shows such a device, as constructed by Messrs. **Ferranti.**[1] The resistance itself consists, in this case, of a glass

[1] See *Electrician*, vol. l., p. 13 (October 24th, 1902).

tube (B) nearly filled with ordinary water, through a small hole under the rubber band A, which keeps the hole closed. The current is led to the two electrodes by means of the plugs (CC) and sockets (cc). The whole is contained in a porcelain handle E, which, besides serving completely to enclose all live parts, enables the voltmeter to be isolated. whenever required, by withdrawing the fuse. Should a short circuit occur inside the voltmeter, the current flowing will be sufficient to boil the water, but this is not detrimental to the device, as the steam can escape through the valve at A, and it has, moreover, the incidental advantage of automatically cutting the voltmeter out of circuit.

Electrostatic voltmeter resistances are also often made of carbon, but unless special precautions are taken, there is always a risk of the carbon disintegrating, under the influence of the high voltage, and so increasing the resistance to an abnormal extent, or even breaking the circuit altogether.

For extra high pressures, say above 20,000 volts, it has been proposed to enclose all the working parts in a bath of oil so as to prevent breakdown. But for such pressures the ordinary arrangement is hardly suitable, and special precautions are necessary as regards insulation, and so forth. One of the latest forms of **Voltmeter for pressures up to 200,000 volts** is that of Jona, which is shown in section Fig. 42. The pressure to be measured is applied to the two terminals A and B, of which the latter is in metallic contact, through the supporting wire (K) with the suspended plate C. The terminal A is joined to a sheet of tin-foil on the outside of the glass containing vessel D, and when electrified this plate induces a charge on another sheet of tin-foil (E), on the inner side of the glass. The plate C is therefore attracted by E with a force dependent on the pressure, and its value can consequently be read on the scale at F.

The shield G, which is in metallic contact with C and

therefore at the same potential, serves to screen the instrument from external influences. The vessel *D* is nearly filled with insulating oil, which both damps the oscillations and increases the dielectric strength. Since the force of attraction depends on the nature of the oil, the instrument should be calibrated with that which is subsequently to be used.

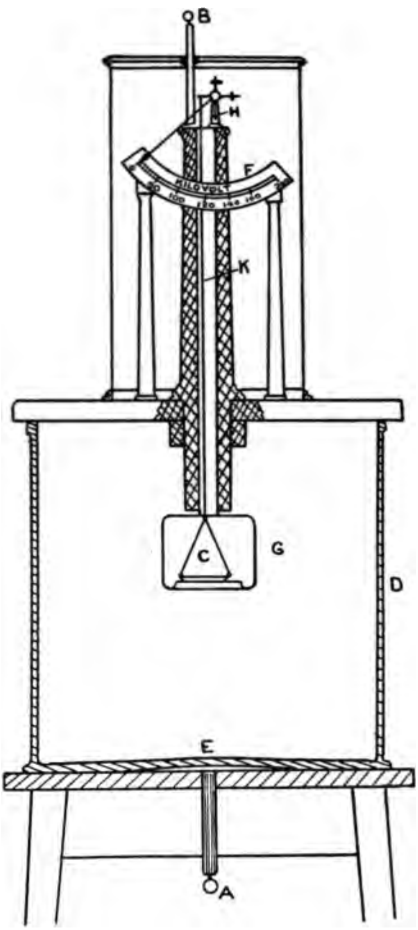


FIG. 44.—200,000 volt Jona electrostatic voltmeter.

The controlling weight *H* is adjustable, and a pair of weights are usually provided, which give two sensibilities, the one double the other. The scale, graduated from about 25 per cent. of the maximum upwards, is almost evenly divided through the working range.

Peukert[1] showed that if a number of **condensers** be connected in series with an electrostatic voltmeter, its range can be increased in any required ratio, just as is done in the case of ordinary voltmeters, by means of series resistances. It is to be remembered that, in this case, the

[1] *Elektrotechnische Zeitschrift*, vol. xix., p. 50.

potential difference at the terminals of each condenser is inversely proportional to its capacity, the voltmeter itself being regarded as a condenser. The fact that the capacity of the latter varies at different parts of the scale, owing to the movement of the pivoted vane, necessitates a special calibration, since the capacity ratio will vary slightly at each point of the scale. This change of capacity is however small, and more serious errors are likely to be introduced by leakage and by external influences.

Although quite unaffected by external magnetic fields, electrostatic voltmeters are very liable to disturbance from **static effects**, such as may be produced, for example, by rubbing the glass front of the instrument to clean it. Since, however, the inside of a conductor cannot become electrified, these effects can be entirely overcome by enclosing the instrument in a metal case, or by coating the inside of the case either with tin-foil, or a conducting metallic paint. The glass window, if large, can be covered either with meshes of tinfoil, gold leaf, or metallic paint, or else, as first suggested by Prof. Ayrton and Mr. Mather,[1] can be coated all over with a transparent conducting varnish. One such varnish is made up as follows: Melt ¼ oz. of transparent gelatine in 1 oz. glacial acetic acid (by heating to 100° C.). Add half this volume of dilute sulphuric acid (1 : 8 by volume). Apply to the glass while still warm. When set hard, cover with a thin coating of transparent acid-resisting varnish. The glass will now be almost as transparent as before, but the film will be quite conducting.

Another source of error to be guarded against when using low-tension electrostatic voltmeters for direct current measurements is that due to **thermo-E.M.F.'s** between the various metallic parts. These are, however, as a rule, negligible except at very low voltages.

[1] Inst. E. E., April 24th, 1894.

To sum up, it may be said that for laboratory work the electrostatic voltmeter is of considerable value, owing to the fact that it can be employed indiscriminately for direct or alternating currents of any frequency and wave-form, and for extra high-tension measurement it forms the only available instrument. In modern central-stations the use of electrostatic instruments is restricted almost exclusively to high-tension boards, where they are often installed either as supplementary voltmeters or as leakage indicators (see p. 180).

POWER MEASUREMENT.

DIRECT AND SINGLE-PHASE ALTERNATING CURRENTS.

The necessary connections for the measurement of power by means of a **wattmeter** on a direct or single-phase system are shown in Fig. 54 (see p. 100). It must be remembered that, if the connections are as indicated in the figure, the power absorbed by the pressure circuit will be included in the wattmeter reading; whereas, if the pressure circuit is connected to the points *a*, *b* (*i.e.* between the current-coil and the generator, instead of between it and the load), the power absorbed by the current-coil will be included, and must be deducted from the reading. It is usually fairly easy to measure the former, either (1) from a knowledge of the voltage and of the resistance of the pressure circuit, or (2) by observing if there is any deflection when no current, except that taken by the pressure circuit, is passing through the current-coil. That is to say the points *a* and *b* are connected across the mains, and any reading (in watts) so obtained must be deducted from subsequent deflections.

It is easy to **compensate** the wattmeter for this latter error by winding alongside the current bobbin, but in opposition to it, a coil connected in series with the pressure winding, and having a number of turns equal to that of the current coil.

The ampere-turns of this auxiliary winding neutralise those due to the pressure circuit current flowing through the current coil.

Two other methods should be mentioned, although they are only of use in special cases. The **three voltmeter method**

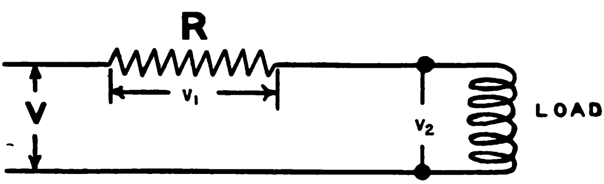


FIG. 45.—Measurement of power by the three voltmeter method.

(due to Prof. Ayrton) is shown in Fig. 45. A non-inductive resistance of R ohms is connected in series with the load, and the potential differences V, V_1 and V_2 are measured, either simultaneously, by means of 3 voltmeters, or successively on one instrument. Then :—

$$\text{Watts} = \frac{1}{2R}(V^2 - V_1^2 - V_2^2).$$

Electrostatic voltmeters are the most suitable, but any pattern can be used, so long as an allowance is made for the current it consumes. When three separate instruments are employed, however, the necessary correction is somewhat difficult. The most accurate results are obtained when V_1 and V_2 are nearly equal, so that it will be seen that the method is cumbersome for most purposes, and is far from reliable, unless extremely accurate voltmeters are employed, owing to the fact that the result depends on the difference of the squares of their readings.

A very similar arrangement is the **three ammeter method**

of Prof. Fleming. This is shown in Fig. 46. If A, a_1 and a_2 represent the respective currents :—

$$\text{Watts} = \frac{R}{2}(A^2 - a_1^2 - a_2^2).$$

In this case the best results are obtained when a_1 and a_2 are nearly equal.

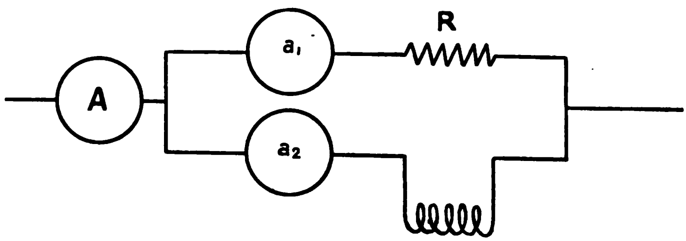


FIG. 46.—Measurement of power by the three ammeter method.

In either of these methods, if R is unknown, its value can be replaced in the formula by $\frac{\text{volts}}{\text{amps.}}$, by the addition of an ammeter or a voltmeter as the case may be. Many modifications of these two methods, which are equally applicable to direct and alternating currents of any power-factor, will suggest themselves for special purposes.

TWO-PHASE CIRCUITS.

A two-phase system may be treated as two single-phase circuits, as regards power measurement. If the load is **balanced**, one wattmeter (W_a, Fig. 47) is sufficient; its reading being doubled to give the total power. If the load is **unbalanced**; a second instrument (W_b) is added, and the sum of the readings on W_a and W_b represents the total power. In a three-wire two-phase system, the two lines a and b are combined into one, but the wattmeter connections are unchanged.

THREE-PHASE CIRCUITS.

If the "**neutral point**" **is accessible,** three wattmeters, with their current coils connected, one in each line, and their pressure coils between each line and the neutral point, will give the total power, however unevenly the load may be distributed between the three phases. If the load is balanced, three times the reading on one wattmeter, so connected, will

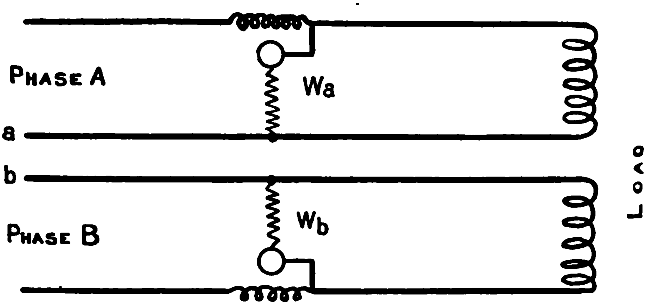


FIG. 47.—Measurement of two-phase power with two wattmeters.

give the total power.[1] In the majority of cases, however, the **neutral point is not accessible,** but an artificial neutral point can be formed by means of three equal resistances, connected in "**star,**" and to this either one or three wattmeters, according to whether the load is balanced or unbalanced, can be connected up as before. The former arrangement is

[1] It should be remembered that with a star connected load the phase voltage (*i.e.* voltage between any line and the neutral point) is :—

$$\frac{\text{line voltage}}{\sqrt{3}} = \frac{\text{line voltage}}{1{\cdot}732.}$$

With a delta (or mesh) connected load the currents in each side of the delta are :— $\frac{\text{line current}}{\sqrt{3}}$. The power in a balanced three-phase system is :—watts $= \frac{\text{line volts}}{\sqrt{3}} \times$ line amperes $\times\ 3 \times \cos\phi$. If unbalanced the power is the sum of the watts expended in each of the three phases.

shown in Fig. 48 and the latter in Fig. 49. In each case the pressure circuit of a wattmeter forms one arm of the star resistance.

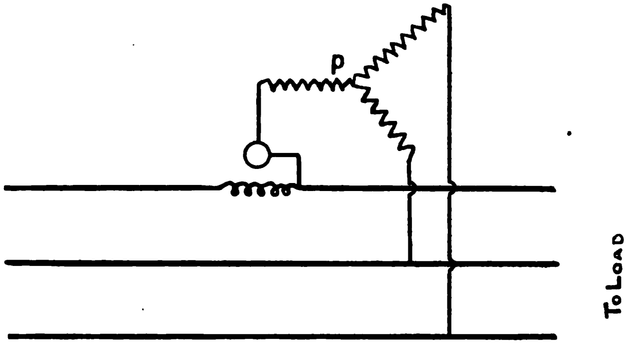


Fig. 48.—Measurement of three-phase power on a balanced load with one wattmeter.

In the case shown in Fig. 48, it is essential that the resistance of the arms should be equal, but when three watt-

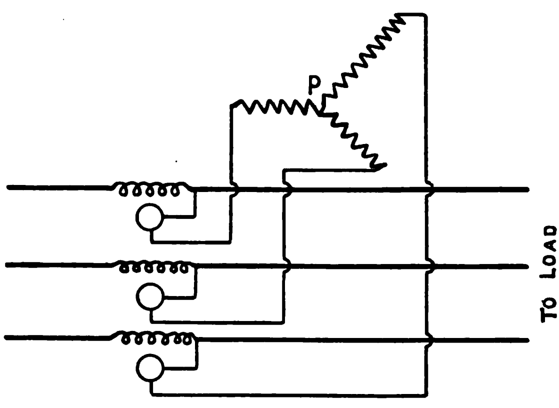


Fig. 49.—Measurement of three-phase power on an unbalanced load with three wattmeters.

meters are used (Fig. 49), this is unnecessary, and the sum of the three readings will always represent the total power. This leads to a simplification of the method. Suppose that the

wattmeter in the middle line is replaced by another, having a pressure circuit of much lower resistance than the other two; this wattmeter will indicate less power than before, and the other two more than before, but the sum of the three will still indicate the true total power. Pushing this reasoning still further, the resistance of the middle wattmeter can be reduced to zero, and in fact it may be removed altogether, the point p being connected direct to the middle line.[1] The connections will then be as shown in Fig. 50, and the sum of the readings on the **two wattmeters** will give the

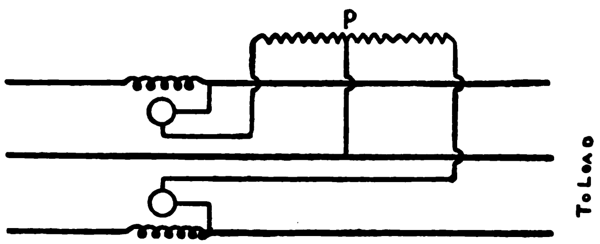


FIG. 50.—Measurement of three-phase power on a three-wire unbalanced load with two wattmeters.

true power at all power-factors, whether the load be balanced or unbalanced.

If the load is balanced, and the power-factor 0·5 (*i.e.* if ϕ is 60°), one wattmeter will indicate zero, and the other will carry the whole load. For power-factors of less than 0·5 the one instrument will read in the reverse direction, and must be *subtracted* from that of the other. To enable these negative deflections to be read, either the pressure or current circuits can be reversed, as may be most convenient.

The ratio of the two readings thus affords an **indication of the power-factor** of the system (so long as the load is

[1] See Clinker, *Electrician*, August 21st, 1903, p. 743.

balanced). If W_1 and W_2 represent the readings we have (assuming a sine wave):—

$$tan\,\phi = \sqrt{3}\,\frac{W_1 - W_2}{W_1 + W_2}.$$

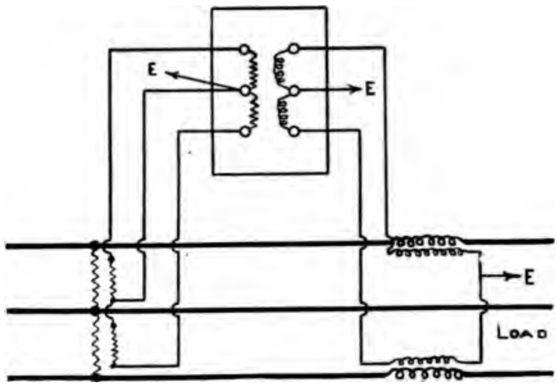
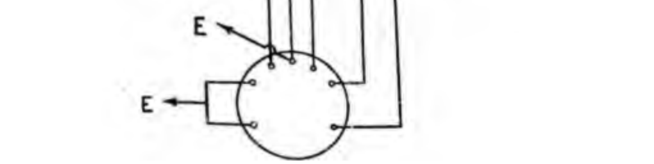


FIG. 51.—Measurement of three-phase power on an unbalanced high-tension load.

Instead of using two wattmeters, whose readings have to be added, the two movements may conveniently be mounted on one dle, so that the pointer indicates the total power (see Fig. 90). high-tension systems, current and potential trans-



52.— — .—Measurement of phase-displacement on a high-tension three-phase three-wire load, balanced or unbalanced (see p. 122).

formers are employed, and it is usual to specify that the secondary windings shall be earthed. Figs. 51, 52, and 53 show the connections for such cases.

In what has been said above, three-wire three-phase systems have been considered, but with a lighting load a **four-wire system** is often employed. The fourth wire performs the function of the middle wire in a three-wire direct current system, and only carries the out of balance current. It is

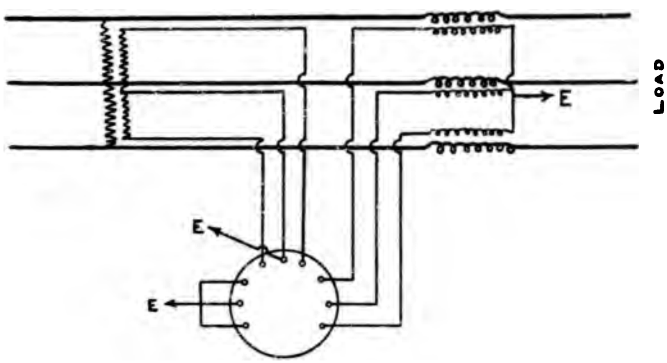


FIG. 53.—Measurement of phase-displacement on a high-tension three-phase four-wire load, balanced or unbalanced (see p. 122).

clear that, in this case, two current transformers are insufficient, since the current in that main which has no current transformer in it may vary without the other two being affected. Consequently, three wattmeters must be used on a four-wire system, or, in the case of a power-factor indicator, an instrument with three coils, and therefore three current transformers, as shown in Fig. 53.

WATTMETERS.

DYNAMOMETER TYPE.

In describing the **Siemens dynamometer** (p. 61) it was pointed out that this instrument could be readily transformed

into a wattmeter. For laboratory work a wattmeter, so arranged, forms a very satisfactory instrument. The connections are shown in Fig. 54, where *CC* represents a coil carrying the main current, and *VC* a coil connected in series with a fairly high resistance (*R*) across the terminals of the load. The field due to the current-coil is thus proportional to the current, and that due to the volt-coil to the pressure. The torque is therefore proportional to amperes $\times$ volts $=$ watts. Since, moreover, the controlling force is proportional to the angle of torsion, it follows that the angle turned through is proportional to the watts.

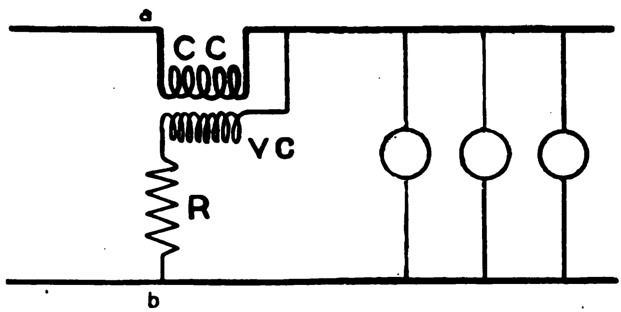


FIG. 54.—Connections for dynamometer wattmeter.

It is immaterial which of the two coils is fixed and which movable, but, owing to the difficulty of leading a large current into the current-coil, it is usually fixed, while the volt coil swings either inside or outside it. Current may be led into and out of the moving-coil, either by means of mercury cups, or by the controlling springs, or, as is more usual, by means of thin silver or copper ligaments.

For **direct-current** measurements it is only necessary that the resistance *R* should have a negligibly small temperature coefficient, and be sufficiently high in resistance to mask the temperature coefficient of the coil itself, which is usually wound with copper wire. With **alternating current** on the other hand, it is essential, in addition to this, that the self-

induction of the pressure circuit should be negligibly small, so that the current flowing through it may be accurately in phase with the volts at its terminals.

If this condition is fulfilled, and the load be non-inductive, the main and shunt currents will be in phase with one another, and the torque will be proportional to $V \times C$. If, however, the main current lags by an angle ϕ behind the line voltage, the torque will be proportional to $V \times C \times \cos\phi$, assuming a sine wave. But this quantity is equal to the "**true power**" transmitted.

But if, owing to its **self-induction,** the current in the shunt circuit lags by an angle a behind the voltage at its terminals, the torque will be proportional to

$$V \times C \times \cos a \times \cos(\phi - a).$$

When a is small, $\cos a = 1$ nearly. Hence:—

$$\text{True watts} = \text{wattmeter reading} \times \frac{\cos\phi}{\cos(\phi - a)}.$$

The error is $100\,a \tan\phi$ as a percentage of the watts or $100\,a \sin\phi$ of the volt-amperes.

It is clear, from this expression, that for small values of ϕ (*i.e.*, for fairly non-inductive loads) the error will be unimportant, but that, with a decreasing power factor ($\cos\phi$), the error increases rapidly. It will be noticed, moreover, that when $a = \phi$ the error disappears, owing to any tendency of the shunt lag to increase the reading, being just balanced by the tendency of the self-induction of the shunt circuit to reduce the current. Further, with a lagging current, when ϕ is greater than a, the wattmeter will read too high and *vice versâ.*

Although, as shown above, it is easy to apply a correcting factor if a is known, it is usually a matter of some difficulty to determine this angle, since it varies with both the frequency and the wave-form of the circuit. In good modern wattmeters intended for use at low power-factors the angle a

is so small, however, that it can be entirely neglected, for all practical purposes, even down to as low a power factor as, say, 0·05 ($\phi = 87°$). Thus, assuming the coefficient of self-induction of the moving-coil circuit to be 0·02 henry (an average value), and its resistance to be 3,000 ohms (say, for a 100-volt wattmeter), the errors at 50 cycles per second will be approximately as follow:—

Power factor	1·0	0·8	0·6	0·4	0·2	0·1
Error per cent. ...	·0	0·15	0·28	0·47	1·03	2·0

It should be borne in mind that a is not necessarily a lag; it frequently happens that the **capacity** of the pressure-circuit exceeds its self-induction so that a becomes an angle of lead. This is particularly the case if the series resistance has been wound double (see p. 30), since the two wires lie close together throughout their entire length, and their capacity is fairly large. The capacity of the volt-circuit can be reduced to a perfectly negligible quantity by subdividing the resistance into a number of sections. If there are n sections, the capacity will be reduced to $\frac{1}{n^2}$ of its original value.

Another, and often still more serious, source of error is that brought about by **eddy-currents** in the metal parts of the wattmeter or its case. Suppose, for example, that one wall of the metal case is close behind the current-coil. The field due to the latter will induce an E.M.F. in the metal, lagging 90° behind the flux, that is to say, lagging practically 90° behind the main current. The eddy-current circuit being fairly non-inductive, these currents will be nearly in phase with the E.M.F. producing them, and will therefore lag by practically 90° behind the main current. When used on a non-inductive load such a wattmeter will show no appreciable error, since the current in the pressure circuit is in phase with

the main current, and consequently nearly 90° out of phase with the eddy-currents. On an inductive load, however, the smaller the power-factor (that is to say, the greater the angle of lag between current and voltage) the more will the current in the pressure circuit get into phase with the flux due to the eddy-currents and, consequently, the greater will be the error.

Fig. 55 shows clearly the comparative effect of eddy-currents and self-induction.[1] Let OE and OC represent, in magnitude and phase, the voltage and main current respectively. The true power is $OE \times OC \times \cos\phi$ (assuming a sine wave). Owing to self-induction, however, the current in the pressure circuit will lag by an angle ϕ behind the voltage as shown by OE' (EE' being the E.M.F. of self-induction, at right angles to OE'). The flux due to the main current OC induces eddy-currents at right angles to itself, as shown by CC'. Assuming each flux to be in phase with the current producing it, OC and CC' may be taken to represent fluxes, and OC' will be the resultant flux. Hence it follows that the instrument, instead of measuring $OE \times OC \times \cos\phi$, actually measures $OE' \times OC' \cos(\phi - \phi_1 + \phi_2)$.

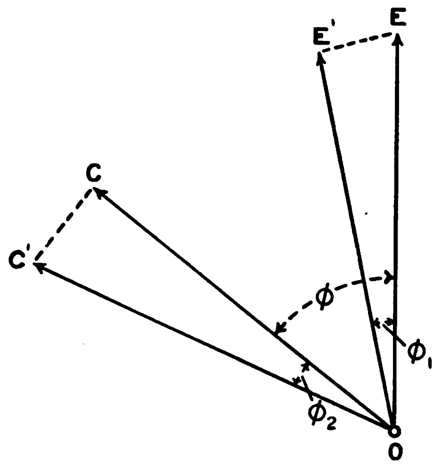


FIG. 55.—Effect of eddy-currents and self-induction in wattmeters.

It will be observed that OE' is smaller than OE, while OC' is greater than OC, so that the error depends mainly on

[1] See Edgcumbe and Punga, *Jl. Inst. E. E.*, vol. xxxiii., part 167, 1904.

the difference between ϕ_1 and ϕ_2; it can be shown, in fact, that if $\phi_1 = \phi_2$, at any given frequency, the wattmeter will read correctly at all frequencies, and with all wave-forms.[1]

It has here been assumed that the eddy-currents are in phase with the voltage producing them,[2] but in practice it is doubtful whether this is an allowable assumption, particularly if they are induced in a low resistance metal such as copper, and, in this case, the adjustment may only be correct for one particular

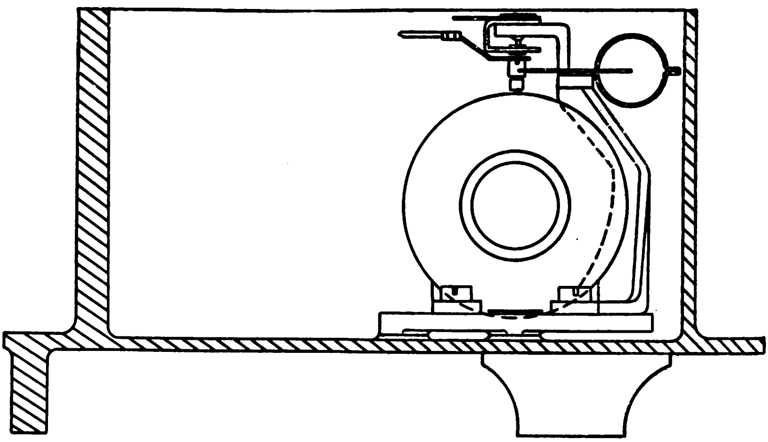


FIG. 56.—Everett-Edgcumbe ironclad wattmeter in section.

frequency. Under these circumstances the only safe course is to reduce the metal parts to a minimum, so as to avoid eddy-currents altogether.

This is much more easily done than is usually supposed. For example, it has been found quite possible by suitable

[1] If W = true power, and w = wattmeter reading, then :—
$W = w \left(\frac{\cos \phi_2}{\cos \phi_1}\right) \times \left(\frac{\cos \phi}{\cos(\phi - \phi_1 + \phi_2)}\right)$ from which it follows that if $\phi_1 = \phi_2$ then $W = w$.

[2] For a full discussion of this point see Dr. C. V. Drysdale's remarks in the discussion on Edgcumbe and Punga's paper, *Jl. Inst. E. E.*, vol. xxxiii., part 167, 1904.

design to fit dynamometer wattmeters, intended for use at power-factors of not less than say 0·2, in cast-iron cases, which have the advantage of shielding them from the effects of external magnetic fields.

The error introduced by such **external fields** often becomes serious, particularly in the case of heavy current instruments, but can be completely overcome by employing a double movement consisting of two fixed and two moving coils arranged astatically one above the other. See Fig. 90.

Fig. 56 shows the iron-clad switchboard wattmeter of Messrs. Everett, Edgcumbe & Co., in section. It is absolutely enclosed in a **cast-iron case,** and that this has no deleterious effect on the working will be gathered from the following figures, taken at about half-load on a 7-kilowatt wattmeter :—

Power factor.	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9	1·0
Error in per cent. of max. reading.	+ 1·8	+ 0·3	− 0·2	− 0·3	− 0·5	− 0·6	− 0·6	− 0·5	− 0·4

In order to avoid eddy-currents in the main winding itself, this should, as far as possible, be laminated. In heavy-current instruments these eddies become of considerable importance, and are difficult to avoid, so that for this reason amongst others, it is usual, above 500 amperes, to employ **transformers or shunts.** The question of the use of transformers is dealt with on p. 134, so need not be discussed here.

It is convenient, for many purposes, to be able to vary the range of a wattmeter by shunting the current coil. Owing, however, to self-induction, the reading of an ordinary wattmeter, so shunted, will depend on the frequency and waveform of the circuit. The error can be reduced in three

ways: (1) by connecting a non-inductive "idle" resistance in series with the current coil, so as to reduce the self-induction of the circuit; (2) by making the self-induction of the shunt equal to that of the current coil; (3) by making the lag, due to self-induction in the volt circuit, equal to that in the current coil, when, as shown in Fig. 55, the instrument will read correctly at all frequencies and with all wave-forms. The objection to the first method is that the necessary drop of volts over the shunt becomes large, unless the working forces are kept very small. The second arrangement is perfectly satisfactory, but is somewhat difficult to carry out in practice; and has the further disadvantage of a high temperature coefficient, unless special precautions are taken to avoid it. The thread method has been successfully employed by Mr. A. C. Heap, but the necessary adjustments are somewhat laborious, particularly if several ranges are required in the volt circuit also.

A further objection to the use of shunts is that the instrument cannot be insulated from the circuit under test, which is often an important consideration. All things considered, then, it may be said that the use of transformers (p. 134) is much to be preferred for increasing the range of wattmeters.

Owing to the fact that the field due to the current coil is, as a rule, enormously greater than that of the volt coil, it follows that, in certain positions of the latter, an E.M.F. will be induced in it, many times greater than that producing self-induction. This **mutual-induction** is often regarded as a source of error, but a little consideration will show that since the E.M.F. so produced is 90° out of phase with the main flux, the current induced in the volt coil will be 90° out of phase with the main current (assuming the pressure circuit to be non-inductive), so that no torque can be thereby produced. If, however, the pressure circuit possesses appreciable self-induction or capacity, an error due to mutual induction may occur. The

zero type of dynamometer, in which the coils are always at right angles to one another, is free from mutual induction errors under all conditions. For the same reason double wattmeters (p. 98) are often arranged with their current coils at right angles.

Practically all that has been said above with reference to Siemens dynamometer instruments applies equally to the **deflectional type,** which are, at the present day, much more used than the zero pattern.

In these instruments the moving-coil is capable of a larger angular movement (say 90°) and carries a pointer passing over a scale, usually so graduated as to read direct in watts, kilowatts, or horse-power, as the case may be. The motion is opposed in any of the usual ways, but generally by a spring.

As a rule the volt coil swings inside the fixed current coil, but in Mr. Heap's instrument, with a view to reducing the self-induction of the current coil to a minimum and increasing that of the volt coil, a small spherical current coil is used, outside which swings a comparatively large volt coil.

In the case of the Siemens dynamometer, the torque is strictly proportional to the product of the two currents, that is, to the watts, since, when equilibrium has been established, the moving coil is always in precisely the same position relatively to the fixed coil. In a deflectional instrument, on the other hand, the relative position of the two coils is different at every point of the scale. That is to say, the instrument does not follow a "**straight line law,**" and the scale divisions will be of varying length.[1]

Several devices have been suggested for this purpose. Messrs. **Siemens and Halske** employed at one time a current winding which gave a practically radial field in which the volt coil swung. Fig. 57 shows the arrangement. The main current, flowing from *A* to *B*, splits into two parts, as shown

[1] See p. 8.

by the arrows. The lower half of the volt coil, which swings above this split current coil, is shown in section at *VC*. The lines of force at *D* and *E*, due to the current coil, form circles round its conductors, and so cut the sides of the volt coil in such a way as to produce a torque. It will be observed, moreover, that the field is radial, so that it is uniform at all parts of the scale, being always perpendicular to the current coil whatever its position.

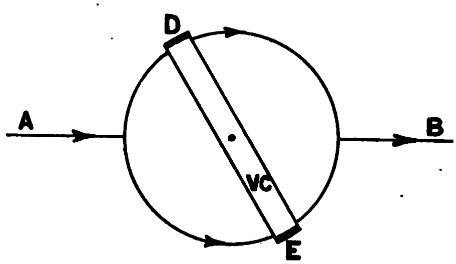


FIG. 57.—Siemens and Halske wattmeter arrangement.

In order to increase the torque the current coil is made double, the current returning by a similar path to that shown, but running above the volt coil instead of below it. The scale obtained with these instruments is evenly divided throughout. The torque is however small and, as a matter of fact, it is quite possible to obtain with the ordinary

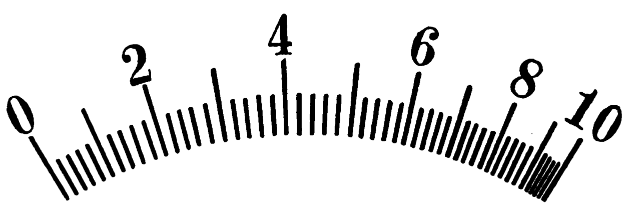


FIG. 58.—Typical wattmeter scale.

arrangement of a fixed coil surrounding a moving-coil, a 90° scale practically evenly divided, or better still (see p. 8) one more open at the beginning than at the end, as shown in Fig. 58.

Various attempts have, from time to time, been made to increase the working forces in dynamometer instruments by the use of an **iron core.** The two latest attempts are those of

Dr. Drysdale[1] and Dr. Sumpner. The former has devised an astatic wattmeter having a current coil wound on a laminated iron core. Assuming the pressure circuit to be perfectly non-inductive, it is essential that the flux due to the current coil should be in phase with the main current. Owing, however, to hysteresis in the iron it is found in practice to be almost impossible to secure this, unless the air-gap is made so large as nearly to do away with any looked-for increase of torque.

In **Dr. Sumpner's wattmeter**[2] (see Fig. 59) the pressure coils (*PC*) are wound on a laminated electro-magnet, having

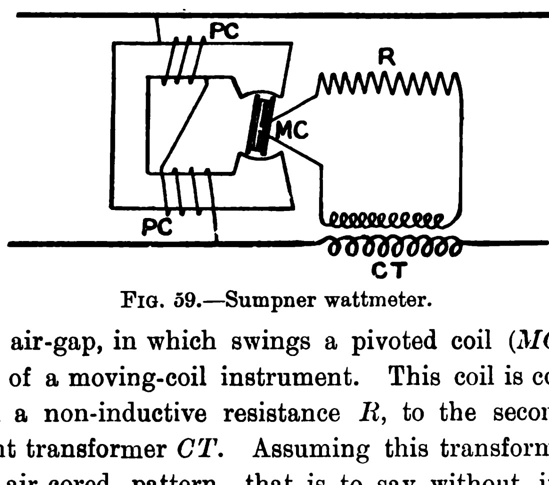


FIG. 59.—Sumpner wattmeter.

a small air-gap, in which swings a pivoted coil (*MC*), as in the case of a moving-coil instrument. This coil is connected through a non-inductive resistance *R*, to the secondary of a current transformer *CT*. Assuming this transformer to be of the air-cored pattern, that is to say without iron loss (see p. 134), its secondary voltage will be 90° out of phase with the main current, and, the secondary circuit being practically non-inductive, the current in the coil *MC* will be 90° out of phase with the main current. It will consequently be in phase with the flux due to the pressure coil *PC*, assuming this latter to be so inductive that its flux lags 90° behind the voltage. The instrument will thus act as a true wattmeter.

[1] *Electrician*, vol. lv., p. 472.

[2] *Jl. Inst. E. E.*, vol. xxxvi., part 177 (1906), and a further paper read in March, 1908.

Unfortunately, similar difficulties arise in this case, as in that of an induction wattmeter[1] (see p. 112), in obtaining a flux 90° out of phase with the voltage. Moreover, in order to reduce the dimensions of the current transformer, and at the same time to shield it from external magnetic fields, an iron core is almost essential, with the inevitable result that the flux, and consequently the secondary voltage, is slightly out of phase with the main current. These two errors are in the same direction, and it thus becomes a matter of considerable difficulty to design a wattmeter on these lines, giving really accurate readings at low power-factors.

INDUCTION OR FERRARIS TYPE WATTMETERS.

In dealing with induction ammeters and voltmeters (p. 81) it was shown that they could be constructed on either of two principles, namely the shielded-pole, or the split-circuit arrangement (depending on the method employed to obtain the necessary lag). With wattmeters, however, the second method is the only one available. As was previously pointed out (p. 83), it is essential for the accuracy of a wattmeter that the flux due to the pressure circuit should be exactly 90° out of phase with that due to the current coil, and the various patterns differ chiefly in the arrangement employed to attain this end.

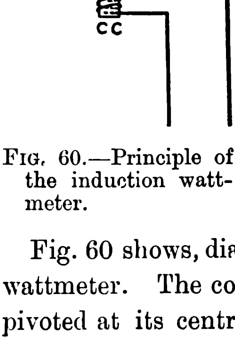


FIG. 60.—Principle of the induction wattmeter.

Fig. 60 shows, diagrammatically, the working of an induction wattmeter. The copper or aluminium disc (D) which is lightly pivoted at its centre, carries a pointer, and the movement is

[1] Dr. Drysdale showed in the discussion on Dr. Sumpner's paper (*loc. cit.*) that this instrument is really an induction wattmeter rather than a dynamometer.

controlled by a spring or weight. Assuming the pressure-circuit to be so highly inductive that the flux due to the current in the coil VC lags 90° behind the voltage at its terminals, a current will be thereby induced in the disc, in phase with the voltage (because 90° out of phase with the flux producing it). This induced current is, consequently, in phase with the flux due to the current coil CC, so that the resultant torque is proportional to the product $V \times C$, if the voltage and current of the load are in phase; or to $V \times C \times \cos \phi$, if there is an angular displacement ϕ between them. That is to say the torque is proportional to the true watts.

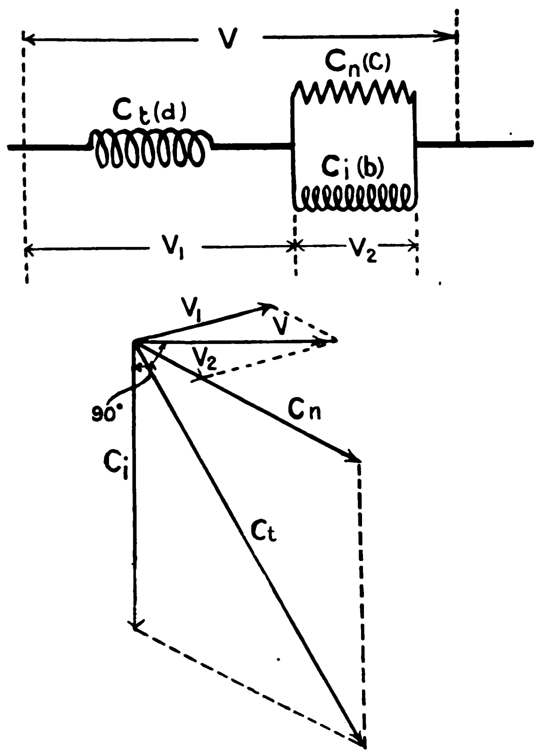


FIG. 61.—Phase-splitting device for induction wattmeter.

In this reasoning several assumptions have been made, which are only partially allowable in practice. For example, owing to hysteresis and eddy-currents in the magnetic circuit of the current coil, its flux will not be exactly in phase with the current. Moreover, owing to copper and iron losses in the

pressure coil, the resultant flux will not be exactly 90° out of phase with the voltage. Hence it follows that it is not easy to insure that the flux due to the volt coil shall be exactly 90° out of phase with that due to the current coil. The effect of any such discrepancy on the reading is similar to that discussed in the case of dynamometer instruments, due to capacity or self-induction in the pressure circuit (see p. 101), That is to say the error is small at high power-factors, and increases rapidly as the power-factor is reduced.

The various devices employed to obtain the necessary angle of **90° between the current and voltage fluxes** may be roughly divided into three groups :—

(1) As shown in Fig. 61, the shunt circuit consists of three parts, namely a choking coil (*d*) connected in series with the pressure coil (*b*), shunted by a non-inductive resistance (*c*). Let C_t C_i and C_n be the respective currents flowing and V, V_1, V_2 be the voltages as indicated in Fig. 61. Then, from the vector diagram, it will be seen that V is the resultant of V_1 and V_2 (V_1 leading nearly 90° ahead of C_t, while V_2 leads by a much smaller angle, owing to this circuit being less inductive). C_t, again, is the resultant of C_n and C_i, and by suitably adjusting the various resistances and self-inductions, the angle between C_i and V can be made exactly 90°. Hence, assuming the flux to be in phase with the shunt current, this flux will lag by 90° behind the impressed voltage, which is what is required. As a matter of fact, in practice, the adjustant is made so that the *flux* lags 90°, rather than the *current*.

(2) A very similar arrangement can be adopted whereby the current flux is made to *lead* by a small angle (a) ahead of the current, so that, although the shunt flux only lags by an angle β, less than 90°, behind the impressed voltage, yet $a + \beta$ can be made equal to 90°, so that the pressure and current fluxes are the required 90° out of phase with one

another. Fig. 62 shows the arrangement. a and b are two series electro-magnets acting on the meter disc or drum, and so arranged that a is very inductive, while b, owing to the idle resistance in series with it, is comparatively non-inductive. The windings are so connected that a drives the meter forward, while b tends to urge it backwards.

In the vector diagram, C_t represents the main current which splits up into C_i and C_n, the latter leading, and the former

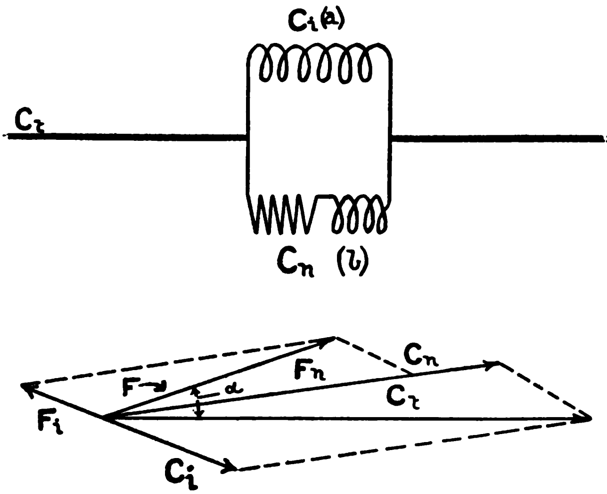


FIG. 62.—Phase-splitting device for induction wattmeter.

lagging with respect to C_t. The magnetic fluxes corresponding to these currents are given by F_i and F_n respectively (the winding carrying C_i being reversed). The resultant flux F, therefore, *leads* by an angle a ahead of the main current.

(3) Perhaps the simplest arrangement consists in increasing the lag in the shunt circuit by the use of a secondary winding short circuited on itself, and situated on the poles of the shunt electro-magnet. This produces a resultant flux, which can be so adjusted as to be exactly 90° out of phase with the

applied voltage. Fig. 63 gives a vector diagram showing how this is brought about. V represents the impressed E.M.F., and F_S the flux to which the shunt current gives rise. The circuit being made as inductive as possible, the flux will lag by probably 80° or 85° behind V. On the poles of this electromagnet are placed short-circuited secondary windings, in which an E.M.F., V_E, is induced. Since this secondary circuit is short-circuited on itself the induced current (C_E) will be nearly in phase with V_E. The flux passing through the disc is the resultant of the flux F_S and that due to C_E. This resultant is shown at F, and by adjusting the resistance of the secondary circuit, and consequently the value of C_E, the angle between V and F can be made exactly 90°.

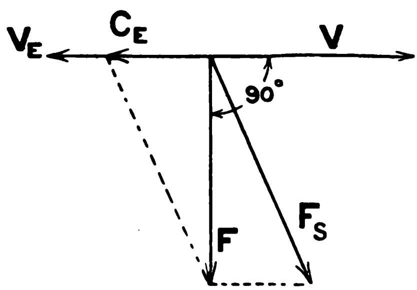


FIG. 63.--Phase-splitting device for induction wattmeter.

As has already been said, the motion of the disc or drum is usually controlled by a spiral spring, which exerts a force proportional to the angle through which it is turned ; so that, if the torque on the disc is proportional to the watts, the scale will be evenly divided throughout. In the case of integrating meters this proportionality is absolutely essential, and to ensure it, the flux due to the current coil must be kept proportional to the current flowing. To this end the air-gap is usually made considerable. In the case of an indicating wattmeter, however, so long as the deflection corresponding to a given load remains constant, exact proportionality is unnecessary (see, however, p. 135).

The scale of such a wattmeter can be made to extend over 360° if desired, and this possibility is often taken advantage of; but it seems doubtful whether any real increase in

accuracy is thereby secured, since in an induction instrument the observation error is, as a rule, small, compared to the various other errors, such as those due to temperature and frequency.

As regards **temperature,** a 10° C. rise or fall will, as a rule, introduce an error of from 1 per cent. to 4 per cent. in the reading, and is difficult to eliminate.

The effect of **frequency** is very marked, amounting, often, to an error of from 3 per cent. to 6 per cent. for a charge of 10 per cent. in frequency, the wattmeter reading low with increased frequency and *vice versâ.*

An induction wattmeter is in general only strictly accurate at a predetermined **voltage,** though the error introduced by small charges is not great, amounting to, say, 2 per cent. for a 10 per cent. rise or fall of voltage.

The effect of changes of **wave-form** is, as might be expected, relatively small, though a "peaked" wave generally makes the wattmeter read somewhat low.

Induction instruments are readily rendered **dead-beat** by means of a permanent magnet acting on the driving disc or drum.

OTHER FORMS OF WATTMETER.

Besides the dynamometer and induction types, several others have been suggested from time to time, but have not, up to the present, been very successful. The most important are the **hot-wire wattmeter** of Mr. M. B. Field[1] and the electrostatic wattmeter of Mr. G. L. Addenbrooke.[2]

The principle of **Mr. Field's** method is briefly that if, of two instruments, one measures the square of the *sum* of the instantaneous values of voltage and current, while the other measures

[1] *Electrical Review,* November 25th and December 2nd, 1898.

[2] *Electrician,* vol. xlv., p. 901 (1900), and vol. li., pp. 811, 845 (1903).

the square of their *difference*, then one reading subtracted from the other gives four times the true power.[1] Fig. 64 shows one method of carrying out this idea. In series with the low reading hot-wire voltmeter (*HW*), which is joined across the shunt *S*, is the secondary of the potential transformer *PT*.

The primary of this transformer is provided with a change-over switch. With the switch connected as shown by the full lines, the voltage at the terminals of the instrument will be proportional to $a + v$, and on reversing (as shown dotted) to $a - v$. Thus the deflections will be proportional to $(a + v)^2$ and $(a - v)^2$ respectively, so that the difference in the readings is proportional to the true watts. In order to obviate having to take two separate readings, Mr. Field proposes to provide two distinct hot-wires in the voltmeter, so arranged that the pointer indicates the difference in their expansions.[2] The transformer has two secondaries, wound in opposite directions, so that one wire measures $(a + v)^2$, and the other $(a - v)^2$, while the pointer indicates $(a + v)^2 - (a - v)^2 = 4\ av$, that is, the true watts.

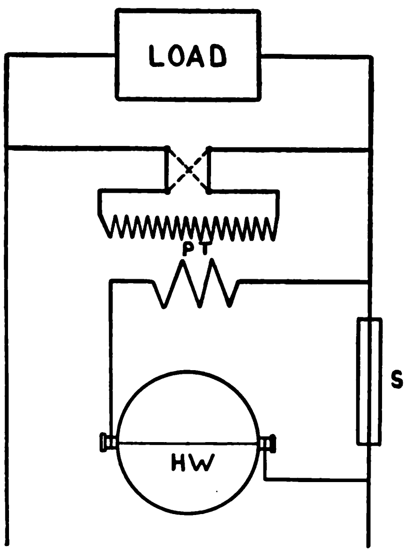


FIG. 64.—Field's hot-wire wattmeter.

Mr. Addenbrooke's electrostatic wattmeter[3] consists

[1] Since $(a + v)^2 - (a - v)^2 = 4\ av$.

[2] See also p. 173.

[3] *Loc. cit.*

of a suspended vane and four fixed quadrants, joined two and two in the usual way. One method of connecting up is shown in Fig. 65, where B and C each represent a pair of fixed quadrants, while A is the suspended vane. S is a non-inductive resistance, giving a drop of about 1·5 volts at full current, and connected in the main circuit. If V_A, V_B and V_C represent the respective potentials above the earth, then the resultant torque is:—

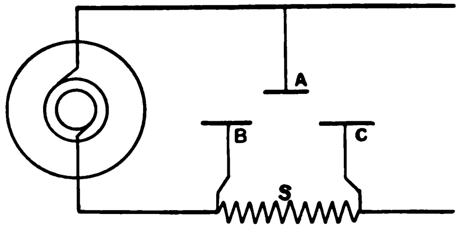


FIG. 65.—Addenbrooke's electrostatic wattmeter.

$$V_B - V_C \left(V_A - \frac{V + V_C}{2}\right).$$

But $V_B - V_C$ is the drop over the shunt, and is therefore proportional to the current, and $\frac{V_B + V_C}{2}$ is the potential of the middle point of the shunt. Thus the expression in the bracket is equal to the voltage of the system, so that the torque is proportional to the instantaneous value of current into pressure, that is, to the watts. It is here assumed that the shunt is perfectly non-inductive.

PHASE-METERS OR POWER-FACTOR INDICATORS.

These instruments may be divided into two groups. (1) So called "**idle-current ammeters**" (or better, "**idle-current wattmeters**") which indicate the wattless component of the power, that is to say $V \times C \times \sin \phi$ (the true power being $V \times C \times \cos \phi$); (2) those measuring either the actual **power-factor or the angular displacement of current and voltage.** Only instruments belonging to the second of these

two groups can properly be described as power-factor or phase indicators, since without a knowledge of $V \times C$ it is impossible to determine either ϕ or cos ϕ, from the indications of instruments of the first group. For many purposes, however, such as regulating the excitation of synchronous motors, they are all that is required.

In speaking of phase-meters it is well to recall the **two distinct definitions of the "phase displacement."** In one of these the angle ϕ is taken as the angle between the points at which the curves of current and voltage cut the zero line in the same sense (see Fig. 66). According to the other

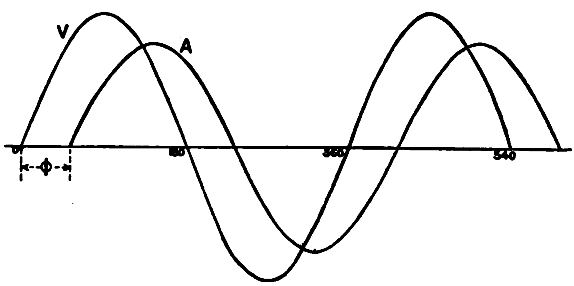


FIG. 66.—Sine waves showing a lagging current.

definition the angle ϕ is given by the equation :—

$$\text{true power} = \text{volts} \times \text{amperes} \times \cos \phi.$$

In the case of sine-waves, the two definitions lead to identical results, but for all other wave-forms, and particularly when those of current and voltage differ in shape, the value obtained for the angle ϕ will depend upon which of the two definitions is adopted.

For practical purposes it is usual to assume that $\cos \phi = \frac{\text{watts}}{\text{amperes} \times \text{volts}} =$ power-factor of circuit, irrespective of whether the angle ϕ has any actual significance or not. In this case, ϕ is sometimes spoken of as the "**power lag**" or

"power lead." In a balanced three-phase circuit the corresponding equation is:—

$$\cos\phi = \frac{\text{watts}}{3 \times \text{amperes} \times \text{phase voltage}} = \text{power-factor}.$$

If the circuit is unbalanced, it is not correct merely to insert the **average** values of current and voltage in this equation. But:—

Power factor ($\cos\phi$) = mean power-factor of the three phases $= \frac{W_1}{3\,A_1\,V_1} + \frac{W_2}{3\,A_2\,V_2} + \frac{W_3}{3\,A_3\,V_3}.$

As will be seen later, an instrument is available which indicates this mean value direct (p. 122).

Idle-current wattmeters.—This form of instrument being the simplest to construct, was the first introduced; the phase-indicator," designed by von Dolivo-Dobrowolski, some 15 years ago, being the oldest. It was constructed on the induction principle, and consisted of a wattmeter in which the volt circuit, instead of being made highly inductive, was made practically non-inductive. The result is the same if a dynamometer wattmeter has its pressure circuit made as inductive as possible. The instrument shows no deflection at unity power-factor, and indicates, in fact, $V \times C \times \sin\phi$. Unfortunately the readings are only correct at a given frequency and wave-form.

In three-phase circuits, advantage can be taken of the fact that if A, B and C represent the three lines, the phase-voltage of A is 90° out of phase with the line-voltage between B and C. If then a wattmeter, whether of the dynamometer or induction type, be connected with its current coil in line A, and its pressure coil between B and C, it will indicate $C \times V \times \sin\phi$. Where C is the current in phase A, V the line voltage, and ϕ the phase displacement between current and voltage in line A, the assumption is here made that the voltages are equal, and are exactly 120° apart.

The phase-meter of Messrs. Ferranti is an induction instrument based on this principle. A change-over switch can be supplied, so that the instrument can be employed to indicate at will either the true watts or the wattless component of the power.

True phase indicators.—Owing to the fact that the indications of the instruments so far described are at best only relative, and give no indication of either the power-factor or the phase displacement, in nearly all modern installations true phase indicators are provided. If, in a single-phase dynamometer wattmeter having a perfectly inductive pressure circuit,

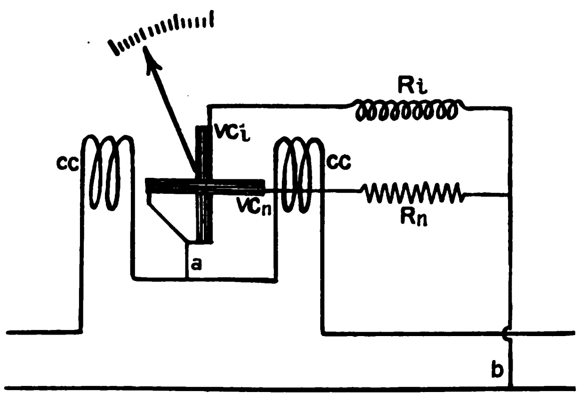


FIG. 67.—Single-phase power-factor indicator.

the spring control be replaced by one in which the torque depends on voltage × current, the deflection will vary with cos ϕ only, and will be independent of both V and C.

Such an instrument is shown in Fig. 67. It resembles an ordinary dynamometer wattmeter, except that, instead of a single moving-coil controlled by a spring, there are two similar coils fixed to the spindle at right angles to one another. The one is connected in series with an inductive resistance (R_i), and the other with a non-inductive (R_n). The current is led into these coils by strips exerting as small a torque as possible.

If the voltage and current are in phase with one another the pressure coil VC_i will experience no torque, and VC_n will set itself parallel to the current coils CC. If, however, the main current lags behind the voltage, the coil VC_i will begin to experience a torque, while that exerted on VC_n will decrease. The moving system consequently takes up a new position for each value of ϕ.

It is clearly unimportant what may be the actual angle between the coils, or the angle of lag in the VC_i circuit, so long as the scale is empirically calibrated. The indications are independent of the value of the current in the coils CC, but the accuracy depends on the ratio of the currents in VC_i and VC_n, and the phase displacement in VC_i, remaining constant. By carefully designing the choking coil R_i, it is possible to keep the current ratio fairly constant for moderate changes of pressure, but the value of the current in R_i depends very largely on the frequency and the wave-form of the applied voltage. Such instruments, therefore, are only suitable for central station use where both can, as a rule, be regarded as fairly constant.

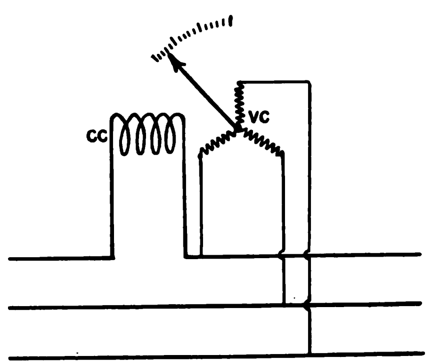


FIG. 68.—Everett-Edgcumbe three-phase power-factor indicator.

To overcome this objection it was proposed by Mr. Punga[1] to utilise the actual phase displacement of a **polyphase system** to obtain the required rotary field. The principle of action of such an instrument (that of Messrs. Everett, Edgcumbe & Co.) is shown in Fig. 68, arranged for a three-phase **balanced** system.

[1] *Helios*, 31 and 32, vol. viii. (August, 1902).

The main current flows through the current coil CC. Inside this is pivoted the moving volt-coils VC, much as in a dynamometer wattmeter, except that there are three moving-coils fixed at an angle of 120° to one another. Each winding is connected through a resistance to one of the three mains, the inner ends of the coils being connected together so as to form a "neutral point."

The working is identical with that of the single-phase instruments just described, except that, as the phase displacement does not depend on a choking coil, the readings are independent of frequency, wave-form and voltage.

For **unbalanced loads** three current-coils, fixed 120° apart, are employed, each connected in a different phase. By putting one or more of these into circuit, either the power-factor of any particular phase or the average for the whole system can be determined (see p. 119). For high-tension circuits, transformers are used, either two single-phase or one three-phase pressure transformer being required.

The instrument is equally applicable to **two-phase systems**, the coils being, in this case, fixed 90° instead of 120° apart.

SYNCHRONIZING DEVICES.

The simplest form of synchronizer consists of an **incandescent lamp**, connected across the contacts of a single-pole switch, connecting the two machines to be paralleled. This arrangement is shown in Fig. 69, where L shows the lamp in question. If the machines (M_1 and M_2) are in phase there will be no potential difference at its terminals (that is to say it will not light up), and the switch can be safely closed. Owing to the indefiniteness of such an indicator an improvement was introduced in the shape of a **synchronizing transformer**, as shown in Fig. 70. This consists of a transformer (T) having a double primary winding, and a single

condary, across which is joined the synchronizing lamp. The indings are so connected that when the machine is "in step" ith the 'bus-bars the lamp is fully alight, and it is then con-

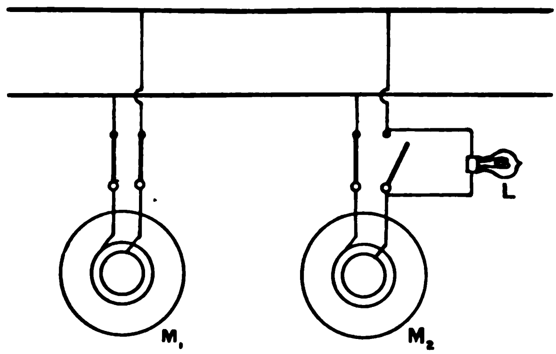


FIG. 69.—Synchronizing lamp.

siderably easier to determine the correct moment for switching in than when synchronism is indicated by the lamp being out. In place of the lamp a dead-beat **volt-meter** is often provided, and is certainly easier to use.

In the case of the transformer (*T* Fig. 70), assuming that the ratio of primary to secondary turns is $1 : n$, and that there is no magnetic leakage, the secondary voltage, as measured by the voltmeter, will vary between zero and $2n$ times the primary, according to the phase relation existing between the generator and the 'bus-bars. The correct moment for

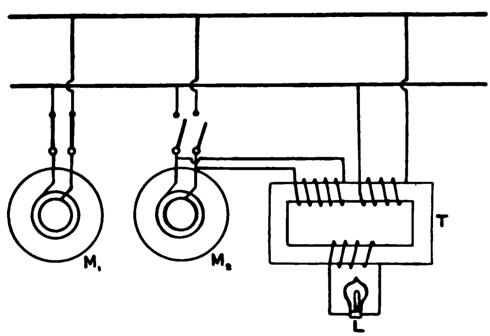


FIG. 70.—Synchronizing transformer.

switching in will thus be when the voltmeter needle reaches its maximum deflection.

A little consideration will show that, when the generator and 'bus-bars are exactly out of phase with one another, the resultant flux is *nil*, assuming no magnetic leakage. That is to say, a condition has been reached equivalent to an infinitely large secondary load. As a result, either the transformer will be burnt out, or the fuse blown.

To make such an arrangement practicable, therefore, both the magnetic leakage and the primary turns must be increased to such an extent as will provide sufficient self-induction to reduce the current, when the machines are out of phase, to a reasonable amount. This is found in practice to entail so large a transformer that its cost is quite as high as that of two separate transformers, each with one primary and one secondary.

In **modern practice**, moreover, the high tension synchronizing bars, which such a system requires, are seldom installed and each generator is usually provided with its own transformer, which often works a voltmeter or wattmeter as well. The secondaries of these transformers are so arranged that, for synchronizing purposes, any two can be temporarily connected in series across the terminals of the voltmeter by means of a plug or switch.

With the ever increasing size of generators all such synchronizing devices are rapidly giving place to "**rotary synchronizers**" or "**synchroscopes**" as they are variously called. These instruments are, in reality, special forms of power-factor indicator, from which they differ chiefly in that the pointers are free to revolve, and that no scale is provided since only the point corresponding to coincidence of phase (*i.e.*, synchronism) is required.

If, in the case of the power-factor indicator shown in Fig. 67, the coils *C C* are wound with fine wire and connected to the

terminals of one alternator, whilst the wires marked *a* and *b* are connected to another, supposed to be giving the same frequency, then the pointer will indicate the phase relation of their E.M.F's. If, on the other hand, there is a slight difference of frequency, this phase relation will be continuously changing, and the pointer will revolve at a speed depending on this difference. It will, in fact, make one revolution for each complete cycle gained by one generator over the other. The direction of rotation, moreover, will depend on which of the two alternators is running at the higher speed.

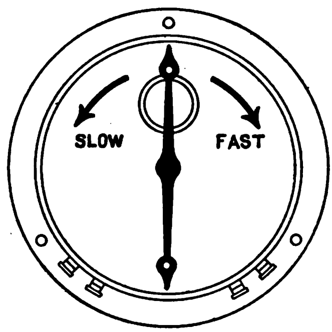


FIG. 71.—Rotary synchronizer.

The synchronizer devised by Mr. Paul M. **Lincoln** works on this principle. The coils *CC* (Fig. 67) are wound on a laminated iron horse-shoe magnet, and the moving-coils (VC_i and VC_n) on a laminated armature mounted on a spindle running in ball bearings, and carrying the pointer. The resistance R_n consists of an incandescent lamp, and R_i of a choking coil.

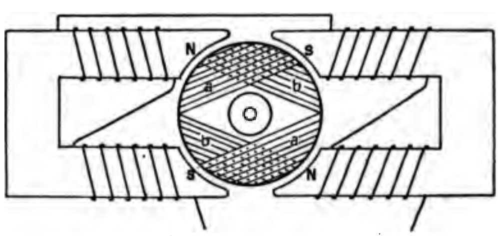


FIG. 72.—Stator and rotor of rotary synchronizer.

The **Everett-Edgcumbe Rotary Synchronizer** is shown in Fig. 71, and the connections in Figs. 72 and 73. The rotor carries a two-phase winding, the coils *a a* being connected in series with one another, and with a non-inductive resistance, whilst the coils *b b* are connected in series with a choking coil,

the two circuits being joined in parallel across the terminals of one of the alternators. By this means a lag of some 85° is produced between the two currents, and a nearly uniform rotary field is the result. In the earlier forms of instrument, the stator carried a similar two-phase winding, on a circular laminated core surrounding the armature. In the later patterns, however, a single-phase stator is employed, consisting of four coils on a four-pole core, as shown in Fig. 72. These windings are joined in series, so as to give alternate north and south poles, and are connected to the station 'bus-bars either directly, or through a transformer. The rotor

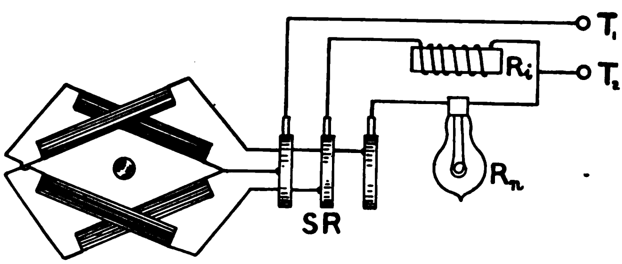


FIG. 73.—Connections of rotary synchronizer.

connections are shown in Fig. 73, one pair being connected through the left-hand slip-ring to the terminal T_1, and the other end through the right-hand slip-ring and lamp R_n, to the terminal T_2. The other windings are similarly connected to T_1, and through the choking coil R_i, to T_2. The rotor is connected to the incoming generator by means of the terminals T_1 and T_2, whilst the stator is joined to the 'bus-bars. Since the rotor makes a complete revolution for each two cycles lost or gained, a double-ended pointer is attached to the spindle, and so set that when standing vertically, as shown in Fig. 71, the machines are exactly in phase.

Provided the engine-driver is sufficiently near the instrument to be able to see the pointer, he can at once tell whether

his generator is running too fast or too slow, and whether by much or little. In large engine rooms, however, this is seldom possible, and a **signalling arrangement** has consequently been provided, which consists of a red or green light shown in the small round opening in the dial, according as the speed is too high or too low. On the rotor spindle is carried a toothed disc, which engages with one or other of two pawls, according to its direction of rotation. These pawls are attached to a vertical arm, pivoted at its lower extremity, which, when the pawls engage, is tilted over, in one direction or the other, and falls by its own weight against a stop. In falling, one pawl is automatically disengaged, whereas the other is ready again to come into action, so that when the rotor reverses the arm is forced to the other end of its path. This arm carries two transparent coloured screens side by side, and is so arranged, that, when it is at one end of its travel, a green screen is opposite the opening in the dial, and is illuminated by the lamp inside the instrument, but so soon as the rotor reverses the red screen takes its place.

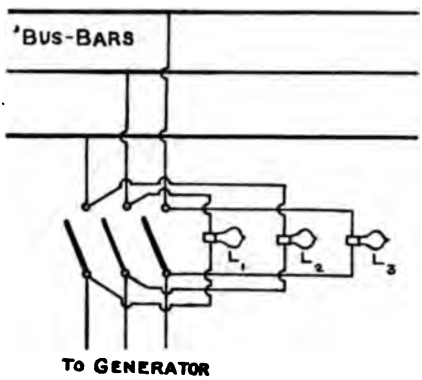


FIG. 74.—Siemens and Halske three-phase synchronizing lamps.

On **polyphase circuits,** it is possible so to arrange the synchronizing lamps that they show whether the speed of the incoming generator is too high or too low. Messrs. **Siemens and Halske** have designed an apparatus on these lines, of which Fig. 74 shows the connections. L_3 is joined up as an ordinary synchronizing lamp, and serves as such, synchronism being indicated by its remaining dark. Lamps L_1 and L_2 are

cross connected as shown. Assuming the generator to be exactly in phase with the 'bus-bars, and the switch to be open, the phase difference between the potentials at the terminals of L_1 will be 120°; similarly for L_2. If now the frequency of the generator be slightly increased, the potentials at the terminals of one of the lamps will be brought more into phase, and of the others less. Lamp L_2, for example, will become gradually brighter, while L_1 and L_3 grow less bright. Thus the light appears to have travelled from L_3 to L_2. A little later on it will have travelled to L_1, and then back to L_3, and so on. If, on the other hand, the frequency of the generator was decreased, the apparent rotation would have been in the opposite direction. Thus L_3 acts as a synchronizing lamp, while the three lamps show whether the incoming machine is fast or slow. A disadvantage possessed by this arrangement, for high-tension work, is that three transformers are required for each generator, since the synchronizing cannot be done on one phase.

The synchronizers described may be taken as typical, others on the market being mostly variations of these. Thus the **Schuckert** is an elaboration of the Siemens and Halske, whilst the **Westinghouse** is similar to the Lincoln, except that both windings are fixed, and a **Z**-shaped core revolves, thus obviating the necessity for slip-rings and brushes.

In conjunction with the increasing use of remote control switching arrangements, **automatic synchronizers** have been employed, particularly in America. Whether they will be largely taken up in this country, where automatic devices are looked upon with somewhat less favour, remains to be seen. These synchronizers consist essentially of three parts, corresponding to the three factors constituting correct synchronism, namely equality of voltage, frequency, and phase. The apparatus, therefore, comprises a voltage relay and a phase relay connected in series, which, provided they have simultaneously

closed a circuit *for a sufficient length of time,* actuate an automatic switch connecting the incoming generator to the 'bus-bars. It is essential that the time element should be introduced, as otherwise it would be possible for the machine to be switched in when momentarily in phase although running at either too high or too low a speed.

FREQUENCY INDICATORS.

The measurement of the frequency of an alternating current is a matter of some difficulty, owing to the fact that most

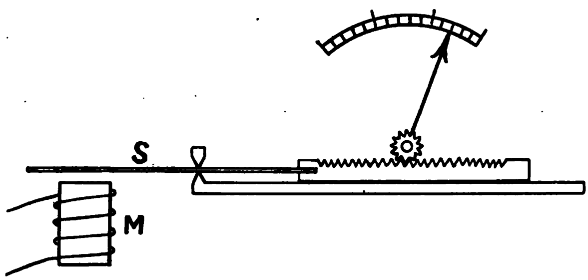


FIG. 75.—Campbell's frequency indicator.

electrical phenomena which are dependent on frequency, are also dependent on wave-form. For example, the earlier instruments were based on the variation of the current in an **inductive circuit** with changes of frequency. They were, in fact, very similar in principle to the power-factor indicator shown in Fig. 67, except that the coils *CC* were wound with fine wire, and connected in parallel with the *VC* circuits, across the mains. The ratio of the currents in VC_i and VC_n (and with it the reading), thus depended on the frequency and wave-form of the applied voltage.

In most modern frequency indicators this arrangement has been abandoned in favour of the **resonance principle,** the first practical instrument being that of Mr. Albert **Campbell.**[1]

[1] Paper read before Physical Society, *Phil. Mag.*, August, 1896.

In this apparatus (see Fig. 75), the end of a steel spring (S), of variable length, is placed near the pole of an electro-magnet (M) carrying the current whose frequency is to be determined. If the free period of vibration of the reed is equal to half the frequency of the current, the reed will be set in resonant vibration, the cycle of operations being as follows: As the current (and with it the flux) increases to a maximum, the reed is attracted towards the pole, and springs away again as the flux falls to zero. The flux then increases in the opposite direction, and again attracts the reed, which is, at that moment,

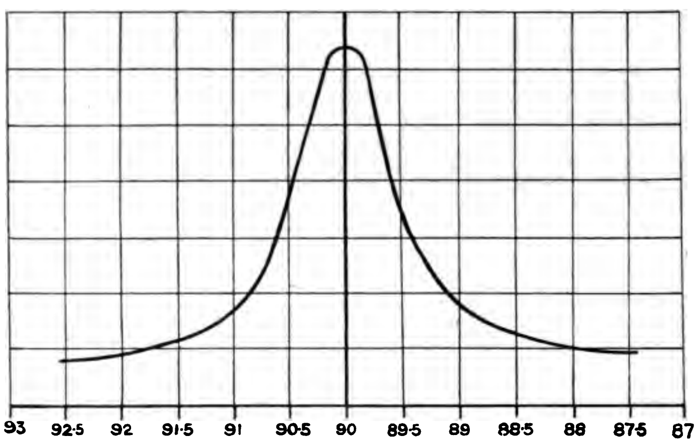


FIG. 76.—Amplitude of vibration of tuned reed.

ready to swing towards the electro-magnet of its own accord. The amplitude is thus gradually increased with each swing, until the energy dissipated in the reed in molecular and air friction just equals that imparted to it by the electro-magnet.

If the frequency of the current is slightly altered from this critical value, the impulses due to the electro-magnet will occur at unfavourable moments, sometimes too early, sometimes too late, and often at such times as to oppose the motion

of the reed. As a result, the very smallest alteration in the frequency is at once noticeable in the amplitude of the vibrating reed. This is very clearly shown in Fig. 76, which shows the amplitude of vibration of a reed of given length at different frequencies. It will be noticed that a change of frequency equivalent to ½ per cent. alters the amplitude by about 50 per cent.

In the Campbell instrument, the length of the reed is altered until it is heard to be in vibration, and by gradually varying it up and down the point of maximum amplitude can be very accurately determined, by ear. The frequency corresponding to this particular length is shown by a pointer moving over a dial.

It had already been suggested by Professor **Ayrton** in 1889[1] that if a number of steel reeds of different lengths were held in front of an alternating-current electro-magnet, that one whose free period corresponded to that of the current would alone be set in vibration. Dr. R. **Hartmann-Kempf** in 1901 published an account of some researches on an instrument of this kind, and showed that it formed an exceedingly sensitive and permanent frequency indicator.

In one form of instrument, manufactured by Messrs. Hartmann and Braun, a number of tuned reeds are arranged round a circle, and a small electro-magnet connected to the mains is brought successively up to each. Every reed is tuned to correspond to a different frequency, and as the electro-magnet comes up to one particular reed it is set in strong vibration, and emits a distinct sound. The frequency to which it responds can be read on a dial fixed above it.

In another variation constructed by the same firm, two rows of reeds are fixed one on each side of an oblong electro-magnet. The reeds are provided with whitened ends, so that the one which happens to be vibrating can be

[1] *Jl. Inst. Elec. Engs.*, vol. xviii., part 79.

at once detected, and the frequency to which it corresponds read off.

The frequency indicator shown in Fig. 77 (that of Messrs. Everett, Edgcumbe & Co.), differs from this instrument only in that the reeds are arranged round a circular magnet, so that the scale is continuous and uninterrupted. The interval between the reeds shown in the illustration, namely half a cycle, is very convenient, as it enables the frequency to be determined with certainty, to within say $\frac{1}{5}$ cycle. There is, however, a possibility that if the frequency lies exactly between two reeds it might not be possible to see, from a

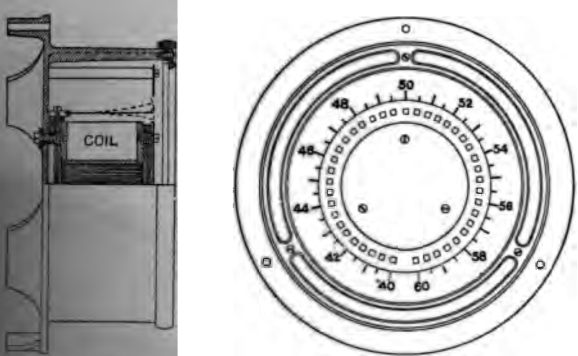


FIG. 77.—Everett-Edgcumbe frequency indicator.

short distance, that any of the reeds were in vibration, so that intervals of a quarter cycle ($\frac{1}{2}$ per cent.) are in many cases preferable.

These indicators can be arranged for frequencies down to 10 and up to 100 cycles per second; above this the range must be increased by the method given below, and the most satisfactory results are obtained between 20 and 60 cycles per second.

It might be thought that a reed vibrating continually at such speed would be liable to deteriorate, but experience with such

instruments, after being in continuous use for years, shows that, so long as the lower ends are securely and unalterably fixed, constancy is assured.

In the frequency indicator due to **Frahms,** the tuned reeds, instead of being individually attracted, as in the instruments so far described, are attached to a common armature which is set in vibration by the electro-magnet, and thus *mechanically* vibrates the reeds, so that the one of corresponding period can be picked out as before.

Any of the vibrating reed frequency indicators just described can be readily used as **speed indicators,** graduated in revolutions per minute. In the case of the Frahms instrument, mechanical impulses can be imparted to it, say, by means of a toothed wheel attached to the rotating shaft, or in the case of turbines and petrol engines, even the vibration of the machine itself is often enough to set a particular reed in resonant vibration.

With an alternating current generator the frequency affords a ready means of determining the engine speed. In other cases a small multipolar magneto-alternator, usually of the induction type, provides sufficient current, at a frequency dependent on the speed, to excite the electro-magnet of the instrument. Sometimes a simple contact-maker is attached to the spindle arranged to give a certain number of "makes and breaks" per revolution. A source of direct current of suitable voltage is connected through it to the frequency indicator, which thus receives an intermittent current at a frequency proportional to the speed to be determined. For example, if there are n contacts on the contact-maker (so that the circuit is closed and opened n times per revolution), then, if the reed marked "p cycles per second" is set in vibration, the speed is $\frac{120\,p}{n}$ revolutions per minute. As a rule, however, the dial is marked direct in revolutions per minute.

A simple means of **doubling the range of a frequency indicator** may be mentioned. It must be remembered that for every complete cycle the reed is twice attracted, once for each *reversal* of the current. If a direct current, equal to the mean value of the alternating current, is sent through the winding at the same time, that is to say, is superposed on it, the effect will be to neutralise one half of the wave and to increase the other half, with the result that the reed only experiences one impulse per cycle, instead of two.

In practice this is done by providing the electro-magnet in the instrument with two windings, one carrying the direct current, and the other the alternating. The latter is used by itself for the lower range, and the two together for the higher. It should be remembered also that a reed will respond, though less vigorously, to a frequency allowing it to vibrate twice per half cycle instead of once.

INSTRUMENT TRANSFORMERS.

When transformers are employed with measuring instruments, it is usually for one of three reasons :—

(1) To obviate the risk of bringing high-tension cables to the instruments, with the possibility of the cases being made "alive";

(2) To simplify the switchboard connections, by only running small wires to the instruments ;

(3) To enable the meters themselves to be placed at a considerable distance from the switchboard.

It may safely be said that above 1,000 volts, either transformers, or cases of insulating material, should always be employed. From the manufacturer's point of view, also, it becomes difficult to construct instruments with windings sufficiently large to carry the very heavy currents often met with in electro-chemical work for example, and it is then usual to

employ transformers, since shunts are as expensive, and not nearly so satisfactory (see p. 105).

In the case of an **ammeter or voltmeter** which can be calibrated in conjunction with its own transformer, no particular care need be taken in the design of the latter, the only error likely to occur being, in fact, that introduced in a current transformer by changes of frequency. The case of a **wattmeter,** however, is very different, and not only is it necessary for the ratio of transformation to be constant, but the primary and secondary currents of current transformers, and the primary and secondary voltages of voltage transformers, must be in phase with one another respectively.

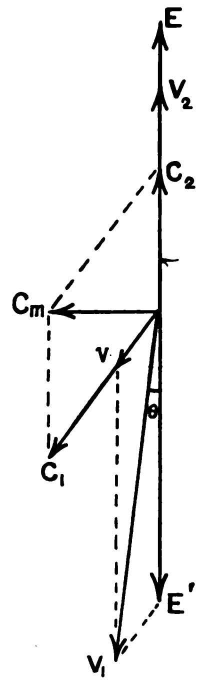


FIG. 78. — Vector diagram of pressure transformer.

Constancy of ratio, while essential in watt-hour meters, is important even in the case of indicating wattmeters when used with varying voltage or varying power-factor, even although the scale is empirically calibrated. As an example, suppose the ratio of transformation to be so variable that, to take an exaggerated case, an increase of 10 watts corresponds, at the lower part of the range, to ·2 in. on the wattmeter scale, whilst at full load it corresponds to ·1 in. Then if, with the full current flowing, the wattmeter reading be reduced (by varying either the voltage or the power-factor) to the lower of the two points mentioned, a current variation corresponding to 10 watts will give ·1 in. change of deflection, whereas for a correct reading the pointer should have moved through ·2 in.

Fig. 78 gives a vector diagram of a **pressure transformer,** supposed to be connected to an instrument having **negligible**

self-induction, that is to say, the secondary current (C_2) is in phase with the secondary E.M.F. (E). The primary and secondary turns are also, for simplicity, supposed to be equal in number. The primary voltage V_1 has to balance the induced E.M.F. E', and, at the same time, to provide an E.M.F. V sufficient to overcome the ohmic resistance of the primary winding. Or, in other words, V_1 is the resultant of E' (that is, E reversed) and V (in phase with C_1). The primary current, in its turn, has to give rise to a magnetising current C_m (leading 90° ahead of the E.M.F. E which it induces), and also to a secondary current, C_2 (in phase with E).

From this it follows that V_1 will always be slightly greater than V_2 (the secondary terminal pressure) and will be out of phase with it by an angle of $180° - \theta$. Thus, on reversing the connections of the secondary winding, the secondary voltage *leads* the primary impressed voltage by an angle θ. Any increase in the magnetising current (C_1 and C_m being thereby brought more into phase) increases this angle, as does also the resistance of the primary winding (since it increases v_1). For this reason, both should be kept as low as possible, and this points to the use of iron of the best quality, and to a good magnetic circuit, with minimum leakage. Further, the secondary current C_2 should be kept small (since v_1 and v_2 increase with it); or, in other words, the transformer should be worked at as light a load as possible.

On open circuit C_2 is non-existent, but, owing to eddy currents and hysteresis, there is a certain **watt loss**, W_o, which may be looked upon as a non-inductive secondary load, and can be represented in the vector diagram by a current, $C_o = Wo/E$. Strictly speaking, then, C_2 = secondary current + C_o (vectorially added if not in phase), so that, even on open circuit, V_2 is always smaller than V_1 and leads by a small angle. In fact, a consideration of the diagram will show that on open circuit the angle θ is actually larger than when

lightly loaded, since C_1 and Cm are more nearly in phase, but, on the other hand, V_1 more nearly equals V_2, and the ratio of V_1 to V_2 is more constant (see Fig. 79).

If, instead of being non-inductive, the instrument connected to the secondary is **inductive**, as will frequently be the case, C_2 lags behind V_2, and it will be seen that the angle θ is thereby increased, but, on the other hand, the difference

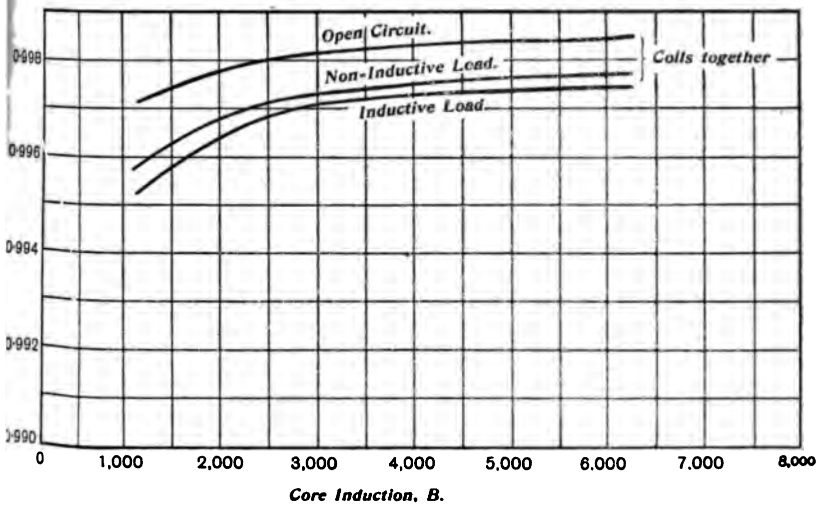


FIG. 79.—Variation of ratio of pressure transformer with load.

between primary and secondary voltages (that is, the ratio error) is reduced.

The magnetising current and ohmic drop are very much magnified in the diagrams for the sake of clearness; for example, the latter would not, in practice, exceed 2 per cent. or 3 per cent. of the primary voltage, and see Fig. 82.

The curves in Figs. 79 and 80 are taken from results obtained by Dr. C. V. Drysdale[1] on a transformer of the shell type, wound for a ratio of 30:150 volts. The core area was

[1] *Electrician*, November 23rd, 1906, p. 201, and Paper before the Phys. Soc., March, 1908.

71 square centimetres, and the length of the magnetic path 35·3 centimetres. The "non-inductive load" consisted of a 150-volt voltmeter of 2,400 ohms resistance, and the "inductive load" of a choking coil of 900 ohms impedence at 50 cycles, at which frequency the tests were made. It will be noticed that although the inductive load was some 2½ times greater than the non-inductive, the ratio was but very slightly worse.

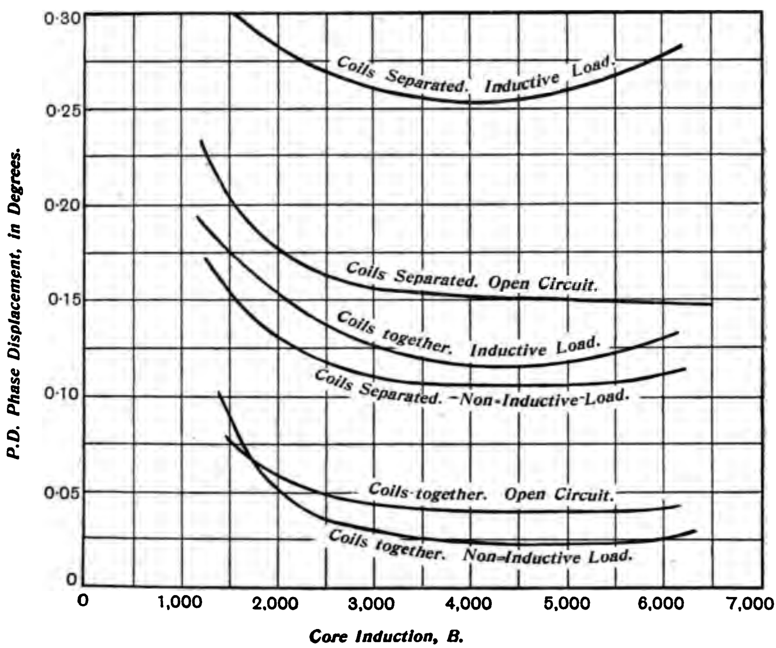


FIG. 80.—Phase-displacement in pressure transformer at different loads

. 80, however, which indicates the effect on the phase dis-ement (θ), shows that in this respect the reverse is the case, hase error being considerably greater with the inductive

ıen the **magnetic leakage** was increased by separating ils, the error was found to be very much greater. With

this particular transformer, a maximum induction of about 5,000 would seem to give the best results (Fig. 82). At this point, the ratio, even in the worst case, is somewhat better than 0·997, which corresponds to an error of only 0·3 per cent., if the primary and secondary voltages are assumed to be in strict proportion to the number of turns. At this same induction, the phase displacement is 0·21° for an inductive load, and ·025° for a non-inductive load. For all practical purposes, then, both the phase and ratio errors in well-designed voltage transformers can be entirely neglected.

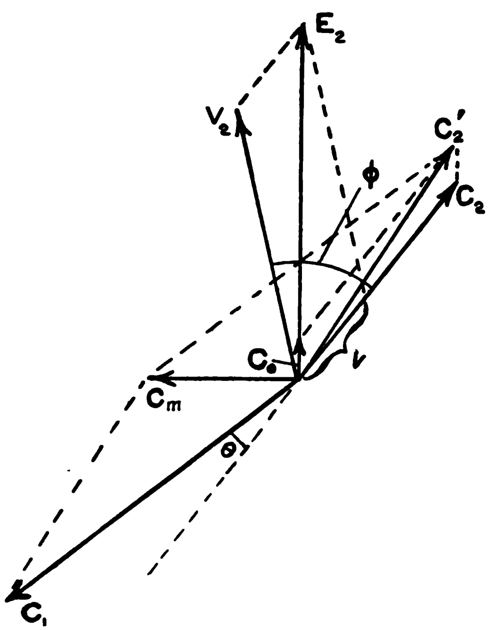


FIG. 81.—Vector diagram of current transformer.

Fig. 81 shows the state of affairs in a **current transformer** supposed to be wound with an equal number of primary and secondary turns, and to be working on an **inductive load**, as would be more or less the case when used with most ammeters or wattmeters. The primary current C_1 gives rise to a secondary current, C'_2, and a magnetising current, C_m, the latter being, in fact, the resultant of C_1 and C'_2. At right angles to C_m, and lagging 90° behind it, is a secondary E.M.F., E_2. C'_2 is actually the resultant of the secondary current C_2, and the core loss current C_o, (where $C_o = \frac{Wo}{E_2}$

and is looked upon, as in the case of voltage transformers, as a non-inductive secondary load).

The secondary E.M.F. E_2 gives rise to (*i.e.*, is the resultant of) the secondary voltage V_2 and the ohmic drop V in the secondary winding, in phase with C_2. The angle ϕ between secondary current and voltage depends solely upon the inductive nature of the instrument to which the transformer is connected.

The **errors introduced by a current transformer**[1] are :—

(1) Phase error (represented in the diagram by θ) ;

(2) Ratio error.

These errors are due to :—

(1) Magnetising current ;

(2) Core losses (hysteresis and eddy-currents) ;

(3) Magnetic leakage ;

(4) The ohmic resistance of the secondary.

Fig. 82 shows how the first three of these quantities vary with the induction.

To realise the effect of the **magnetising current**, it must be remembered that although C_1 and C_2 have so far been spoken of as currents, the vectors actually represent ampere-turns; consequently the disturbing effect of C_m (which is a fixed number of ampere-turns) can be reduced to any required extent by increasing the number of **primary and secondary ampere-turns**. A limit is, however, reached, owing both to the increased ohmic resistance of the secondary winding, and to the fact that a longer iron circuit is required to accommodate the larger coils. In practice, 300 or 400 ampere-turns are found sufficient for use with a single ammeter, 600 or 800 for a wattmeter, and 1,500 for a watt-hour meter or where a number of instruments have to be worked off a common transformer. The magnetising current tends to increase θ,

[1] See also F. Punga, *Electrician*, vol. 51, p. 1008, Oct. 9th, 1903.

but, except when connected to a very inductive instrument, the ratio is but little affected by it.

The **core loss** C_o, on the other hand, being 90° out of phase with C_m, has precisely the opposite effect, and increases the ratio error, except when used with a very inductive instrument; θ, however, is practically independent of the core loss, being, if anything, improved by it on an inductive load.

Magnetic leakage between primary and secondary has an effect equivalent to the removal of a certain number of turns

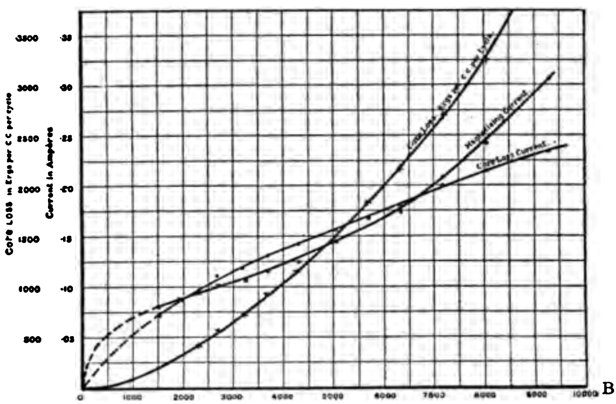


FIG. 82.—Variation in magnetising current and core loss with the induction.

from the secondary, to form a choking coil in series with it. As a result, both the secondary current and E_2 are increased, and with them, C_m and C_o. The lag ϕ also becomes greater, owing to the increased self-induction of the secondary circuit.

The **ohmic resistance** of the secondary, to which V is proportional, is equivalent to an increased instrument resistance, and hence entails an increase of E_2 and, with it, of C_m and C_o.

The instrument itself, whether ammeter or wattmeter, should have as small an impedence as possible. In the case of an ammeter, constancy of ratio being unimportant, **self-induction**, far from being detrimental, may actually decrease the frequency errors; but with a wattmeter, the self-induction

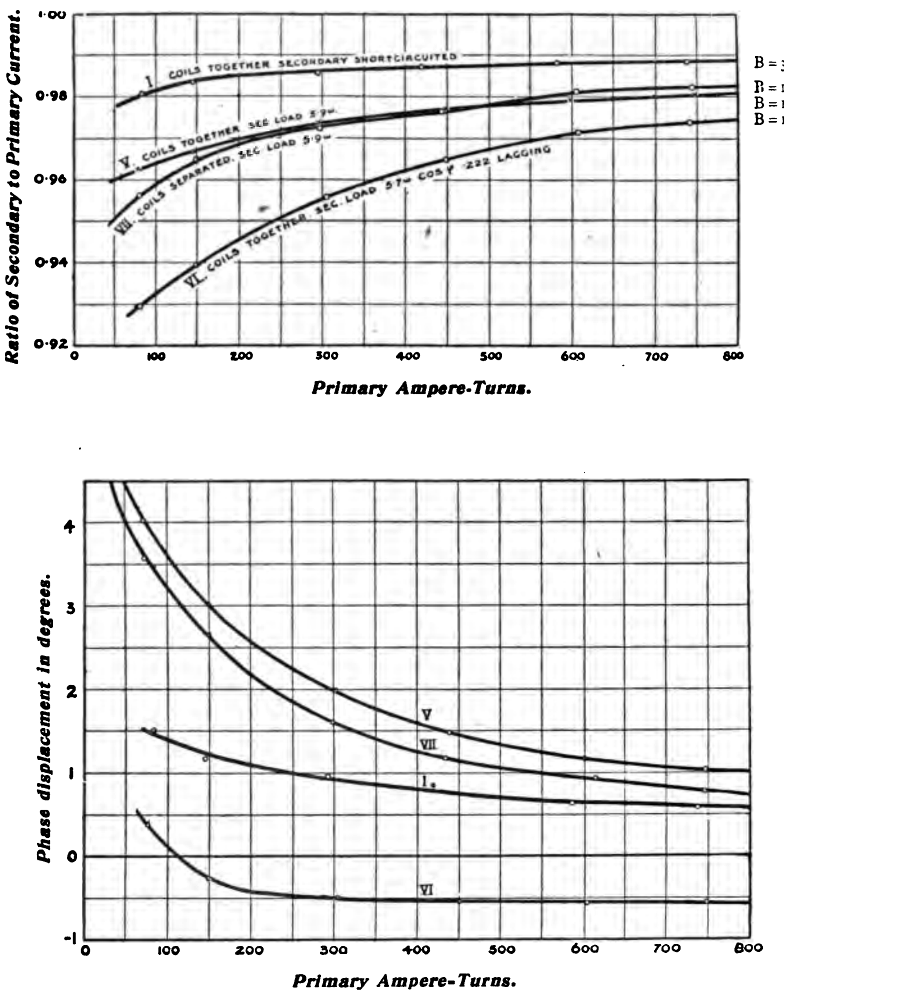


FIG. 83.—Variation in ratio and phase-displacement in current transformer at different loads.

should be reduced to a minimum, since any increase of ϕ will bring about an increased ratio error (see Fig. 82).

These various points are well shown in the curves in Fig. 83, which are taken from results obtained by Dr. Drysdale,[1] using the same transformer as before, but wound, in this instance, as a current transformer with a 5 : 5 ratio. The induction corresponding to full load (in all cases 750 ampere-turns) is given against each curve in Fig. 83. Fig. 83 shows that with the secondary short-circuited the **ratio variation** amounts to about 1·2 per cent. from one-third full load upwards, and when connected to an instrument having a resistance of 5·9 ohms, the ratio error varies from 2 per cent. to 3 per cent., while with an inductive load of equivalent impedence, it amounts to from 2½ per cent. to 5 per cent.

Fig. 83 also shows the corresponding **phase displacement**. On short circuit this varies from ·6° to 1° (from one-third load upwards), whereas with a non-inductive load of 5·9 ohms, it varies from 1° to 2·3°. The effect of a reduction in the phase displacement with an inductive load is well seen in the lowest of the upper curves in which not only is the displacement negative at low loads (that is to say, lag instead of lead), but it is practically constant.

This result is brought about, as will be seen from Fig. 81, by an increase of ϕ, and a corresponding decrease of θ. Unfortunately, however, this does not provide a solution of the phase displacement difficulty, owing to its bad effect on the constancy of ratio (see Fig. 83).

In these experiments of Dr. Drysdale only about half the available space was occupied by the winding itself, so that some slight improvement might be brought about; but in practice, particularly with high tension apparatus, the insulation takes up so much room that the possible improvement would be small.

So far it has been assumed that the **frequency** remained

[1] *Loc. cit.* (p. 137).

constant. Any increase is accompanied by an increase of E_2, and with it of C_2 and C'_2. C_2 and C_1 are, however, usually so large compared with C_m that a very small increase of C'_2 is enough to reduce C_m sufficiently to restore the balance, and in well-designed transformers having not less than 800 ampere-turns, the effect of frequency over a range of from, say, 40 to 60 cycles per second is negligible.

The four main points to be attended to in the **design of current transformers** for use with wattmeters, and in a lesser degree, with ammeters, are :—

(1) A large number of primary and secondary ampere-turns (say, 800).

(2) Low magnetic induction (say, $B = 1{,}500$ at full load).

(3) Well closed magnetic circuit with as few joints as possible.

(4) Minimum magnetic leakage.

In a well-designed current transformer, the following may be taken as **average results** at 50 cycles per second[1] (compare Fig. 82) :—

Difference between ratio of turns and ratio of currents, 0·5 per cent. to 2·5 per cent.

Constancy of ratio throughout useful range, 2 per cent.

Phase displacement between primary and secondary currents (θ), 0·5° to 1·5°.

Core loss component (C_o), 0·3 per cent. to 0·8 per cent. of secondary ampere-turns.

Magnetising component (C_m), 1 per cent. to 1·5 per cent. of secondary ampere-turns.

The **effect of the ratio error** on the accuracy of a wattmeter is directly proportional to that error (see also p. 101). A **phase displacement** of $\theta°$ **produces a percentage error** of $100 \tan \phi \sin \theta$, where ϕ is the angle of lag or lead in

[1] See also L. Wild, *Electrician*, February 16th, 1906, p. 705, and C. V. Drysdale, *Electrician*, November 23rd, 1906, p. 201.

the main circuit. Thus, for example, assuming a phase displacement of 1°, the error on a non-inductive load will be 100 tan 0 sin 1 = 0, whereas with a lag of 30° (corresponding to a power-factor of 0·87) the error is 100 tan 30 sin 1 = 1 per cent. With a lag of 60° (power-factor 0·5) the error is 3 per cent., and at 80° (power-factor 0·17) 10 per cent. Thus, the extreme importance of careful design in this respect is clearly seen. (See, however, p. 101.)

Since it is impossible to wind less than one turn on the transformer limb (a bar passing through the transformer is equivalent to one turn), the minimum possible number of ampere-turns is equal to the current, and consequently, the limits in the case of the transformers already mentioned (p. 140) will be, 300 amps., 800 amps., and 1,500 amps. respectively. Owing, however, to the fact that the insulation of a single conductor occupies very little space, it is usually possible to increase the ampere-turns by 30 per cent., or even 50 per cent. without enlarging the core. At the same time it must be remembered that the secondary turns have to be increased in the same proportion.

Above 2,000 amps. the transformers become somewhat unwieldy, and various devices are in use for **reducing the number of "effective" ampere-turns**. The simplest consists in dividing the primary conductor into two parts of which only one passes through the transformer. Messrs. Siemens and Halske have further introduced an arrangement whereby this adjustment can be accurately made and which, at the same time, shields the transformer from the effects of external magnetic fields. Fig. 84 shows the arrangement. A core of double-E shape is threaded on to the primary conductor, which is bent back on itself to form an inverted U. If the areas of *a*, *b*, *c*, *d* are all equal, the resultant effect on the core, and consequently on the secondary winding ($\acute{S}$) on the middle limb, will be *nil*. If,

however, the area of *a* and *d* be reduced by slotting through the conductor, more current will flow through *c b* than through *a d*, and the *difference* will magnetise the central limb, thereby inducing an E.M.F. in *S*. In this way

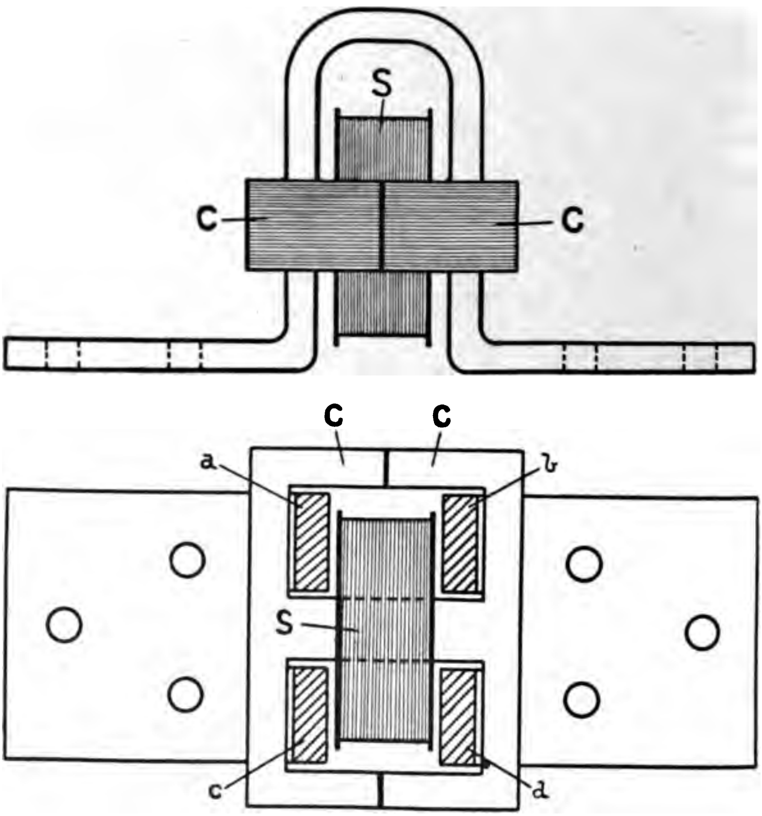


FIG. 84.—Siemens and Halske current transformer.

it is possible to adjust the ampere-turns to any required value, and the outer iron shell effectively shields the secondary from stray magnetic fields. Except for laboratory work, however, this last consideration is of small importance, and an objection to all such arrangements is that, owing to

unequal heating, the distribution of the current is somewhat variable.

RECORDING INSTRUMENTS.

In its simplest form, a recorder consists of a measuring instrument whose pointer carries, at its end, a pen filled with ink, and resting on a paper "chart," which is continuously moved forward by means of a clock. The chart is divided in one direction to represent time, and in the other amperes, volts, etc., as the case may be.

Simple as such an arrangement would appear, the design of a satisfactory recorder is a matter of considerable difficulty. In the first place, owing to the fact that the pen must rest upon the paper, the **friction** is considerable, and in order to overcome it the force exerted by the movement has to be increased with a corresponding decrease in electrical accuracy, Secondly, the pen must contain a comparatively large amount of ink, enough for at least three to four days' use, which means a variable weight at the end of the pen-arm, as the ink is used up. The **pen**, as well as being easily filled, must be so arranged that the ink is not spilled in the event of sudden movements of the pointer. The chart-driving **clocks** are often a source of trouble, owing to the large force which they are called upon to exert, more particularly when driving band charts.

Undoubtedly the first really satisfactory recorder was that of Messrs. **Elliott** Bros. Of the electrical portion of this, in common with others, little need be said, Any of the movements previously described can be adapted to a recording instrument, provided the working forces are sufficiently large; it is in the various mechanical details of construction that one instrument is chiefly distinguished from another.

In the Elliott recorder, which has undergone but little alteration since its introduction in 1896, continuous, or band

charts are employed. A roll is fixed above the clock between centres, and the chart is gradually drawn through the recorder, by means, either of a sprocket-wheel engaging in holes along one edge of the chart, and driven by an 8 day clock, or by friction rollers driven in the same way. The paper may be torn off each day, or passed out of the instrument through a slot at the bottom of the case, or provision can be made for winding it up on another spool, as done with.

A simplified method of inserting the chart has recently been introduced. This consists of a receptacle at the top of the recorder, into which the roll of chart is placed and which has below it a hinged "shoot" down which the end of the chart is passed. The electrical movement is fixed in front of this, and is swung out of the way, so that the chart can be inserted without fear of damaging the pen.

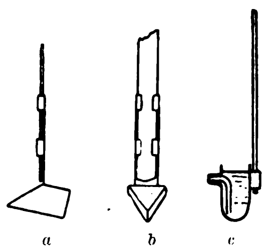


FIG. 85.—Recorder pens.

The pen takes, usually, the form of a very small pointed spoon hinging loosely from the end of the pen-arm, and so weighted as to press lightly on the paper. A disadvantage of this arrangement is that the ink is exposed, and so liable to dry up or spill.

A modified form, the **Dittmar pen**, is shown in Fig. 85 (*c*). It consists of a small vessel, to the bottom of which dips a capillary tube, ending in a carefully rounded point, resting on the paper. The ink is drawn up by capillary attraction, and is not liable to spill, but a disadvantage of this pen is that the fine tube, sooner or later, becomes clogged and is difficult to clean. It is also somewhat heavy.

A simpler form of pen is also shown at *a* and *b* (Fig. 85). The ink is well closed in, but, at the same time, the pen is easy to fill, owing to the fact that it is open on the side nearest to the operator and, for the same reason, is readily cleaned. In

the Everett-Edgcumbe recorders, which embody this pen, the **pen-arm** to which it is attached is distinguished by extreme flexibility, so much so in fact, that it can be almost bent back on itself without harm, thus preventing any chance of damage through rough handling, and at the same time giving a light and constant pressure on the chart.

When the quantity to be recorded is very variable, as for example, in the case of a **traction recording ammeter**, it is found that, unless the pen is large, the supply of ink is insufficient to last more than about 24 hours. To overcome this Messrs. Elliott, in some of their instruments, have adopted a suggestion, due originally to Mr. A. P. Trotter, and place, parallel to the chart, but at right angles to its direction of travel, a narrow trough full of ink. Into this a fine capillary tube, carried on the end of the pointer, dips. The arrangement is shown in Fig. 86. The ink is drawn up the tube by capillary attraction, and, as it remains always full, the weight of the pen does not vary, which is a matter of considerable importance. Should the tube become clogged, it is best to throw it away and replace it by a new one, owing to the extreme difficulty of cleaning it. The ink trough also acts as an efficient damper, and so long as the ink is renewed sufficiently often to prevent its becoming thick, the arrangement works satisfactorily, but requires attention.

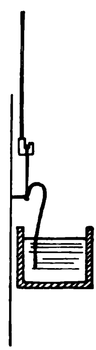


FIG. 86.—Elliott inking trough.

Various attempts have been made to do away with ink and its attendant evils altogether, and at the same time, to eliminate the friction between pen and paper. One of the earliest suggestions in this direction was to allow a **spark, from an induction-coil,** to jump from the end of the pointer through the paper chart to the clock-drum. The paper is thereby pierced with a number of minute holes, and so leaves a record

of the position of the pointer. Unless, however, the paper is very thin, the spark has a great tendency to pass through it where it has been already pierced, instead of at right angles to the drum. A recorder on this principle has been developed by Messrs. Siemens and Halske.

Messrs. Gans and Goldschmidt some years ago introduced a recorder in which the pointer carried at its end, in place of the usual pen, a **sharp steel point**. Every few seconds this point was forced down on to the paper chart by means of an electro-magnet, the circuit of which was closed by the driving

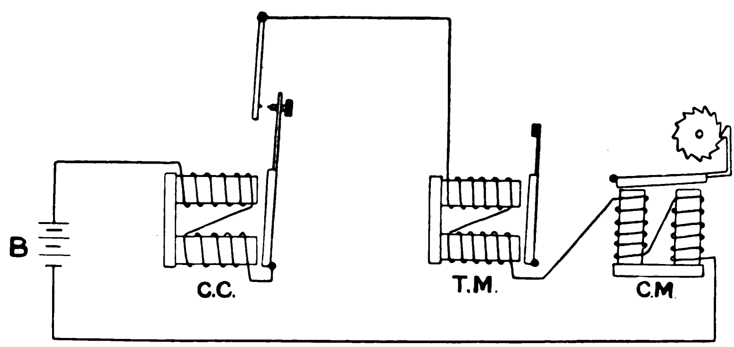


FIG. 87.—Inkless recorder circuit.

clock, and thus made a small indentation in the chart and left a permanent record in the shape of a series of dots. In place of the sharpened steel, a lead point, marking on prepared paper, has been suggested. In a modification of this arrangement, due to Messrs. Siemens and Halske, a piece of **carbon paper** is laid under the chart, which consists of transparent tissue paper, so that a black dot is obtained for each record.

Perhaps the most complete and carefully worked out system of recorders is the **inkless synchronized pattern**. In these not only is ink eliminated, and with it all friction between pen and paper, but any number of recorders, on a switchboard for

example, can be worked from a single controlling clock. Moreover, all being electrically interlocked, they work absolutely synchronously as regards chart timing.

Fig. 87 shows the general arrangement of the circuit when a battery (B) is used to actuate the system. At fixed intervals, usually every five seconds, the controlling clock CC closes the circuit for a fraction of a second. The current flows in series through the chart-driving magnet CM, and the tapping magnet TM. The former moves the chart forward by a definite amount, and the latter makes the record.

The **controlling clock** is shown in Fig. 88. The pendulum (P), of which for simplicity only the upper part is shown in the diagram, makes two swings per second, that is to say it travels from right to left once every second. In so doing the pawl A moves forward the toothed wheel W, on which it rests lightly, one tooth per second. The teeth are so shaped that the pawl, in moving from side to side, normally just passes under the lower end of the upright C, which is pivoted at B. But every fifth tooth is shallower than the rest, so that A engages with the lower end of C, and pushes it clear of the projection D. As a result, the arm E, which is pivoted at F, falls by its own weight. At right angles to E is an arm carrying a flat spring (G) at its extremity.

The arrangement is such that when E falls, G presses on the pendulum, whereas when E is supported by C, the pendulum swings clear of it. The force exerted by G, due to the weight (M) carried by E, provides the driving force necessary to keep the pendulum swinging. Just before the latter comes to the end of its stroke (each time E is released), the spring carrying arm, which follows the pendulum, makes contact with the platinum-tipped screw H and thus, as shown in Fig. 87, closes the battery circuit. The working current flows through the coils KK, which are thereby energised and attract the armature carrying H at its end. This

attraction is sufficient to throw *E* up again, and the support *C*, which is pressed against *D* with a light spring, holds it there, so that the cycle of operations repeats itself,

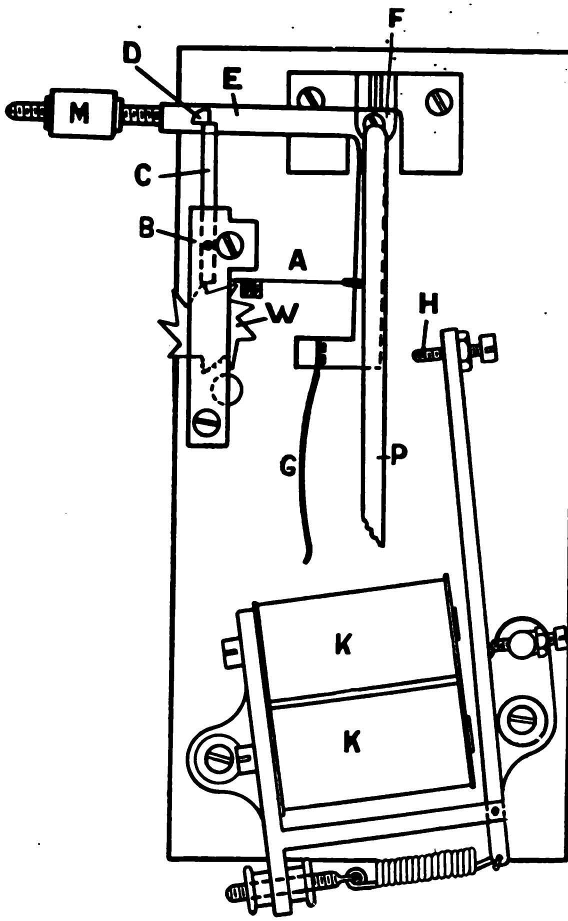


FIG. 88.—Controlling clock of inkless recorder.

the clock being thus self-winding. This timing device, which is due to Mr. Hope-Jones, and forms the basis of his well-known "synchronome" system of electric clocks, may appear

complicated, but, in reality, the simplicity is remarkable, and the contacts being rubbed together with considerable force, keep themselves clean and require no attention.

The **recorder itself** (Fig. 89) consists of a moving-coil, moving-iron, or dynamometer pattern movement, according to circumstances, that illustrated being of the astatic "Universal" type described on p. 67, and at the end of the arm is a steel point *A*, which swings freely between the tapping bar *B*, and the typewriter ribbon. An electro-magnet (not shown in Fig. 89 but seen at *TM* in Fig. 87) attracts *B* and presses it on to the point *A* which in its turn makes a dot on the chart *d* through the typewriter ribbon. This dot occurs exactly under *A*, wherever it may be at the moment, and as the pointer is perfectly free except at the instant of recording, the accuracy depends simply on that of the instrument itself, and is almost as great as in an indicating instrument.

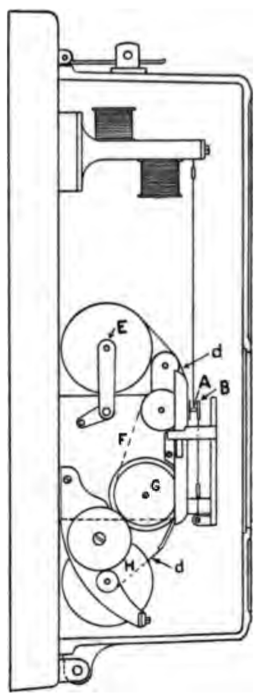


FIG. 89.—Inkless recorder.

The chart, which takes the form of a roll some 60 ft. long, is placed between centres at *E* (Fig. 89). It is provided along one side with a number of holes, into which pins, carried by the endless chain *F*, are caused to engage. This chain is driven by the wheel *G*, which is itself moved through a definite angle by the electro-magnet *EM*. each time the momentary current flows, as shown in Fig. 87. The chain is preferable to a sprocket-wheel, since, by its means, a straight drive is obtained, and at the same time the diameter of the driving-wheel can be greatly reduced. After

passing under the recording point. The chart is wound up on the spindle from which it can be removed as required.

It will thus be seen that, apart from the increased accuracy attainable through doing away with the pen, the whole system is entirely automatic, and so long as the charts are replaced once a month no attention whatever is required. When there are several recorders in an installation, they can all be run from one controlling clock, being connected in series with one another, with the advantage that the timing of the charts is absolutely identical. This will be the case even if the chart speeds of the individual recorders are different, some being, perhaps, arranged for a speed of 1 in. and others of 6 in. per hour.

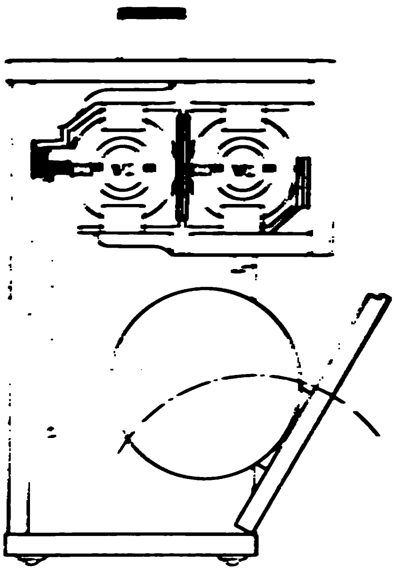


Fig. 69.—Everett-Edgcumbe Astatic portable recording wattmeter.

When the load is very variable, a record every second, instead of every five seconds, is often preferable, and can be easily arranged. In this case, contact is made at *H* (Fig. 68), at each stroke of the pendulum instead of at every fifth stroke. When more convenient, instead of the battery *B*, a tapping off a resistance connected across the mains is used.

In the recorders so far described, roll charts, lasting 7 or 30 days, are provided, but in many cases, it is preferred to have **shorter charts** requiring renewal every **24 hours**, and many makers, accordingly, construct recorders specially

arranged for this purpose. In most of these instruments a drum makes one revolution in 24 hours, and to this the chart, some 12 or 18 in. long, is fixed. The driving clock is usually enclosed inside the drum, so as to be thoroughly protected from dust.

In order to facilitate re-charting, the drums in portable recorders are frequently so arranged as to swing out behind the case (see Fig. 90), and in switch-board instruments either to hinge or slide downwards, clear of the pen.

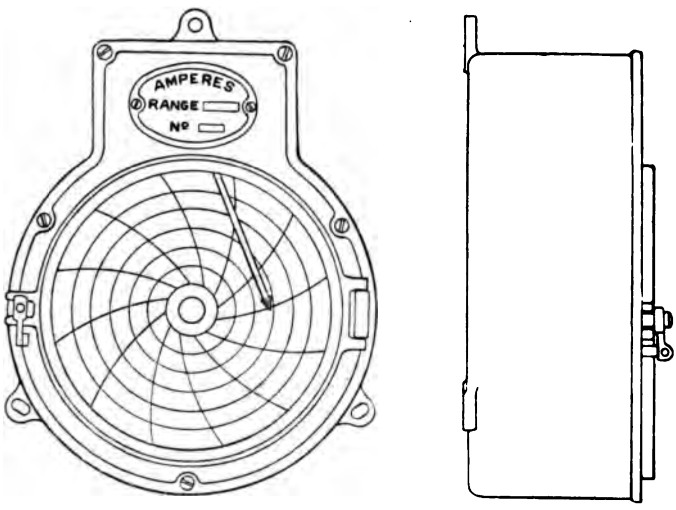


FIG. 91.—Circular chart recorder.

Fig. 91 shows a recorder (the Everett-Edgcumbe "disc" pattern) in which the chart, instead of taking the form of a long strip, consists of **a disc which rotates once in 24 hours.** The hours are marked round the circumference, and the circles represent the scale divisions (volts, amperes, watts, etc.). The scale is $2\frac{1}{2}$ in. long and the entire record is visible. When space is limited, and first cost an important consideration, an instrument such as this proves extremely

useful. Similar recorders due to Prof. Bristol, have been used in America for some years.

All recorders should be thoroughly damped, and for this purpose an oil **dash-pot** is, as a rule, provided, since owing to the large working forces and the weight of the moving parts, a pneumatic or magnetic damper is generally insufficient.

As it is customary to enclose nearly all recorders in cast-iron cases, precautions have to be taken to prevent the opening and closing of the case, for the purpose of inking or recharting, from affecting the reading. This is usually done by covering the movement with a sheet-iron **magnetic shield,** in such a way that, practically, no lines of force pass through the cover itself.

As regards the **electrical portion of recorders,** there is nothing very particular to note, since almost any movement can be employed, provided its working forces are large enough. For **direct currents** all makers, without exception, now adopt moving-coil instruments. For **alternating current** ammeters and voltmeters, Messrs. Elliott employ a moving-coil induction movement, Messrs. Nalder Bros. and Thompson an enlarged pattern of their ordinary moving-iron movement (see p. 66), while Messrs. Everett-Edgcumbe have developed an astatic moving-iron arrangement (see Fig. 89). For **wattmeters** either an induction (*e.g.*, the Allgemeine Co.) or, preferably, a dynamometer movement is employed.

Fig. 90 shows a portable pen type recording wattmeter. For single-phase circuits the two current coils (*CC*) are connected in series, as are also the volt coils (*VC*), in such a way that their polarity is opposed, thus eliminating the effect of external magnetic fields. For three-phase balanced circuits the connections are as shown in Fig. 48, the coils being again in series. In the case of unbalanced three-phase loads, the connections are as shown in Fig. 50, the current coils being separated and placed one in each phase.

A special form of recording instrument was devised some years ago, by Professor **Callendar**, which is useful for accurate scientific work, although it has proved too delicate for industrial purposes. In one form it is adapted to a Wheatstone bridge, and records resistances, the working being as follows:—Across the chart is stretched the slide-wire of a Wheatstone bridge, and the travelling contact carries a pen which traces a line on the chart. The contact, and with it the pen, is pulled along by means of a double clockwork arrangement, which winds an endless cord in one direction or the other, by means of two relays. The pointer of the bridge galvanometer, when at zero, lies midway between two contacts, but so soon as the balance of resistance is disturbed, the galvanometer deflects in one direction or the other, and thereby makes contact and actuates one of the relays just mentioned. This relay, in its turn, couples the clockwork on to the endless cord, so that the contact is drawn along until balance is restored. The pen meantime, traces an accurate record of the position of the contact on the slide-wire, and, consequently, of the resistance. This recorder is also applicable to a potentiometer, and, in fact, to any zero method using a slide-wire, so long as the quantity to be recorded varies slowly.

PYROMETERS.

The electrical pyrometer stands practically alone as a rapid and accurate means of measuring temperatures which lie beyond the range of the ordinary mercury thermometer. The simplicity of the method is so great that, in its cruder forms, it can safely be placed in the hands of any intelligent workman, whilst, with the addition of various refinements, the electrical pyrometer forms by far the most accurate and flexible long range thermometer known.

These instruments may be divided into **two classes**:—

(1) Those in which the heat is applied direct;

(2) Those in which an image of the glowing body is thrown on the thermometer by means of a lens or mirror.

Instruments of the first class may again be subdivided into (*a*) those based on the variation of resistance with temperature and (*b*) those depending on thermo-electric effects.

RESISTANCE PYROMETERS.

The earliest resistance thermometer was that constructed by Sir William Siemens, first for deep sea measurements and later for high temperatures. With a few minor improvements, chiefly in the indicating apparatus, the resistance thermometer

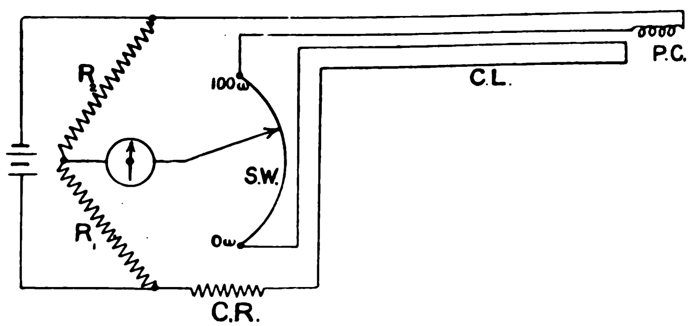


FIG. 92.—Direct-reading resistance pyrometer.

has undergone but little change to the present day. In the **Siemens pyrometer** a differential galvanometer was so constructed that one of its coils was in series with a platinum spiral exposed to the temperature to be measured, while in the other circuit was an adjustable resistance. The value (R_1) which gave a balance when the platinum spiral was cold, was first noted, and after the thermometer coil had attained the temperature to be measured, the variable resistance was again adjusted so as to give a balance. If its value was R_2 the difference $R_1 - R_2$ was a measure of the rise of temperature.

In most modern resistance pyrometers, the differential galvanometer has given place to the **Wheatstone bridge,** either of the ordinary (p. 39) or direct reading (p. 41) form. Fig. 92 shows a very convenient direct reading arrangement. The **platinum working coil** (*PC*), enclosed in a porcelain or other **protecting tube** (see below), is exposed to the temperature to be measured. The ratio coils (R_1 and R_2) are of equal resistance, and a compensating resistance (*CR*) is so adjusted once for all, that, with the platinum coil at a temperature of 0° C., the point of balance, as shown by the galvanometer, is at zero on the slide-wire (*SW*). That is to say (since R_1 and R_2 are equal), the two circuits containing *PC* and *CR* respectively are equal in resistance. If now the temperature of the coil *PC* is raised to, say, 100° C., the equilibrium will be upset, and a new point of balance on the slide-wire must be obtained. Such a point can be found for all temperatures up to the limit of the slide-wire, which, in Fig. 92, is supposed to have a resistance of 100 ohms. As the contact is moved along from the point marked 0ω, resistance is gradually removed from the *PC* circuit, and inserted in the *CR* circuit, and since these two circuits must always remain of equal resistance (R_1 and R_2 being equal), it follows that the number of ohms thus transferred from one circuit to the other, by moving the contact, is exactly equal to the increase in resistance of *PC*, due to its rise of temperature. This temperature can either be obtained from a table, or the slide-wire itself can be graduated direct in degrees.

Since, for many purposes, it is essential to place the thermometer coil at some distance from the bridge, the resistance of the **connecting leads**, which varies with the surrounding temperature, may form a considerable proportion of the whole, and consequently affect the readings. This error is, however, readily avoided by running two compensating leads (*CL*) by the side of the other pair. The change

in resistance (with temperature) of both pairs being ε mately the same, the bridge reading will be unaffectec

Very careful determinations have been made by P Callendar and other observers[1] of the relation cor **temperature and resistance in the case of pla** For small changes, it is usually assumed that the re of a metal is directly proportional to its temperature the wide range required in thermometry, however, this ε tion cannot be made. According to Callendar, a co (t) must be added to the "platinum temperature," often called, to arrive at the true temperature (the "p temperature" being that obtained by assuming tl temperature-resistance curve is a straight line).

Up to 1,000° C. it is found that:—

$$t = k\left(\frac{T^2}{10{,}000} - \frac{T}{100}\right).$$

where T is the true temperature, while k depends chemical constitution of the wire, and is of the order Under these conditions, a thermometer graduated in p temperatures, and correct at 100° C., will read about 7 p low at 500° C. and nearly 20 per cent. low at 1,000° C. tice either a table of corrections is used, or the bridg graduated direct in true degrees.

If **several thermometers are to be used wi same bridge**, it is essential that they should all be i as regards (1) the resistance at 0° and (2) the incr resistance between 0° and 100°. To enable the first cc to be fulfilled, a compensating resistance, CR, adju suit each thermometer, is inserted in the opposite the bridge (see Fig. 92). By this means, the resistanc

[1] H. L. Callendar, Phil. Trans. Roy. Soc. A., 1887; also J. Ha P. Chappuis, Phil. Trans. Roy. Soc. A., vol. cxciv., 1900.

coil can be so adjusted as to fulfil condition 2, and the requisite resistance given to the coil CR.

Thermo-electric Pyrometers.

The first practical thermometer, based on the thermo-electric effect, was that of **Le Chatelier**, who in 1887 proposed the use of a thermo-junction of platinum with an alloy of platinum and rhodium, and, up to the present, no more suitable metals have been found for high temperature work. The E.M.F. of a thermo-electric couple is given by the equation

$$\log e = \alpha \log t + \beta,$$

where e is the E.M.F. in micro-volts; t the temperature of the junction in degrees Centigrade (assuming the "cold ends" of the junction to be at 0° C); while α and β are constants.

With a **platinum / platinum - rhodium** (10 per cent. rhodium) **couple**, temperatures up to 1,600° C. can be measured. For measurements up to 1,400° C. a platinum / platinum - iridium (10 per cent. iridium) couple can be used, and gives a somewhat higher E.M.F.; while, below 500° C., a **copper / Constantan** couple is more sensitive, and sufficiently durable.

The values of α and β in the above equation are as follows, for the couples mentioned :—

Platinum/Platinum-rhodium	$\alpha = 1{\cdot}19$	$\beta = 0{\cdot}52$
Platinum/Platinum-iridium	$\alpha = 1{\cdot}10$	$\beta = 0{\cdot}89$
Copper/Constantan	$\alpha = 1{\cdot}14$	$\beta = 1{\cdot}34$

Below 900° C. a **platinum / platinum - nickel** couple is available, and gives an E.M.F. almost double that of the rhodium combination; an **iron/nickel** couple is also sometimes used, but is not nearly so durable as the platinum combination.

The available E.M.F.'s are in all cases very small. Thus, a platinum / platinum - rhodium couple gives less than $\frac{1}{100}$

volt at 1,000° C. From this it follows that the **galvanometer** used for the purpose of measuring the E.M.F. must be extremely sensitive, and moreover, in order that the resistance of the connecting wires (which varies with the surrounding temperature) may have a negligibly small effect, the internal resistance of the galvanometer must be high. For this purpose, a moving-coil instrument is used, with either a suspended, or very lightly pivoted coil carrying a pointer. The Paul galvanometer described on p. 57 is very suitable for the purpose.

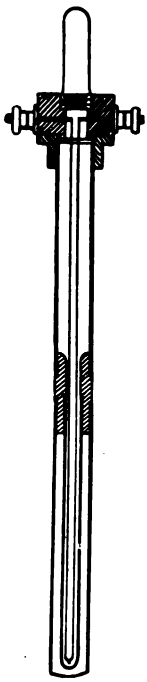


FIG. 93.—High temperature resistance thermometer.

The **thermometers themselves**, whether of the resistance or thermo-electric pattern, require very **careful protection**, both against mechanical injury, and from the corrosive effects of the hot gases to which they are often exposed. For temperatures up to 500° C. a steel sheath is sufficient, but for higher temperatures a porcelain tube is employed. Fig. 93 shows such a thermometer, as constructed by the Cambridge Scientific Instrument Co., for measurements up to 1,400° C. It consists of an outer steel sheath, of which the lower half is removed before inserting in the furnace. The inner tube, which protects the wires is of porcelain, and the head carrying the terminals (four in the case of a resistance instrument, and two for the thermo-electric pattern) is of boxwood.

In most cases the **temperature** of the outer ends of the wires (*i.e.*, the "**cold junction**") can be neglected, in comparison with the much higher temperature of the heated end.

Strictly speaking, however, it should be added to the measured temperature. Messrs. Siemens & Halske in their thermometer arrange a water circulation round the outer end of the apparatus, so as to ensure a low and uniform temperature, but this is, for most purposes, an unnecessary refinement.

Radiation Pyrometers.

These instruments are not themselves subjected to the heat to be measured, and are, consequently, very valuable for **extra high temperature work,** since the destructive effect on a thermometer of temperatures of 1,200° C. or more, is very great, particularly when active gases are present. With radiation instruments, on the other hand, there is practically no limit to the temperatures which can be measured, except for the difficulty of exact calibration.

These instruments can be divided into **two classes**:—

(1) Those depending on the law established by **Wien,** connecting the colour and temperature of glowing "black bodies";

(2) Those based on the **Stefan-Boltzmann** law, that the heat energy radiated from a "black body" is proportional to the fourth power of its absolute temperature.

Pyrometers of the first of these classes are often spoken of as "**optical pyrometers,**" from the fact that the measurement depends on colour phenomena. It is well known that, as the temperature of a body is raised, its colour changes from red to yellow, and finally, to white. Thus the colour affords a rough means of determining temperature. It was shown by **Wien,** however, that greater accuracy was possible by measuring the brightness of one particular colour (*i.e.*, wave-length), which could be separated out, either by means of a coloured screen or by a prism. The colour usually selected is red, and that very considerable refinement is possible with this method,

will be gathered from the following figures, which show the relative intensity of the red rays at various temperatures :—

Temperature Centigrade ...	1000	1200	1800	2000
Relative intensity of red rays	1	10	800	2100

In the case of any particular body, a curve can be plotted, connecting temperature and the intensity of the red rays (or, for that matter, of any particular colour). Wien however, showed that in the case of *all*, so called, "**black**

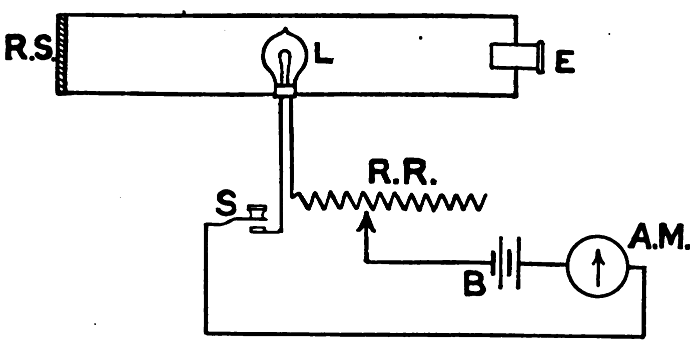


FIG. 94.—Optical pyrometer.

bodies" a definite law existed connecting these two quantities. By a "black body" is meant one which absorbs all rays, of whatever wave-length, that is to say, is neither transparent nor reflecting. Soot is a substance which seems, more nearly than any other, to approach the theoretically perfect "black body." It was further pointed out by Kirchhoff that a **cavity in any heated opaque body** could be regarded as "black," provided the opening was sufficiently small, since, in that case, practically all the rays were of necessity absorbed, except the few escaping through the opening.

It thus becomes possible to apply the optical pyrometer to furnaces, crucibles, and so forth, provided the walls are at the same temperature as the glowing contents. Moreover, most solid substances at high temperatures can, for practical purposes, be regarded as coming within the scope of Wien's law, although, in the case of incandescent gas mantles and the filaments of the new metallic glow-lamps, it is at present somewhat doubtful how far the law is applicable.

The simplest pyrometer of this pattern is that of Messrs. Siemens & Halske, shown in Fig. 94. The object whose temperature is to be measured is viewed through the tube, the eye being placed at *E*. A red screen (*RS*) ensures that the rays reaching the eye shall all be of nearly the same wave-length. In the field of view is a small glow-lamp (*L*) connected to the battery (*B*), through an ammeter (*AM*) and a regulating resistance (*RR*). On closing the switch (*S*), the filament generally appears to be either lighter or darker than the rest of the field of view, and the resistance *R R* is regulated, till the colour is as nearly as possible uniform with it. The ammeter reading is noted, and the corresponding temperature found from a table, or the ammeter itself can be so graduated as to indicate the temperature direct. The point of disappearance of the filament is exceedingly definite, so that considerable accuracy is possible.

In the optical pyrometer of Wanner, a prism is used to obtain the red component of the light received from the object viewed, and the intensity of the light coming from the glow-lamp is varied by optical means.

Of pyrometers of the second class, that is to say those based on the **Stefan-Boltzmann law** (see below), the best known is that due to Professor **Féry.**[1] This instrument is shown in Fig. 95. The open end of a short tube, supported on a pivot

[1] Génie Civil, vol. xliii., No. 5, p. 72; and Journal de Physique, September, 1904.

(*P*), is pointed at the object whose temperature is to be measured; the exact direction being determined by means of the sighting tube (*O*). At the centre two wires are fixed, one of copper and the other of constantan, forming a cross, and soldered at their point of intersection, thus giving a thermo-junction at *J*.

By means of a parabolic mirror (*M*) the rays coming from the furnace (of which one is shown at *RR*) are focussed on to this

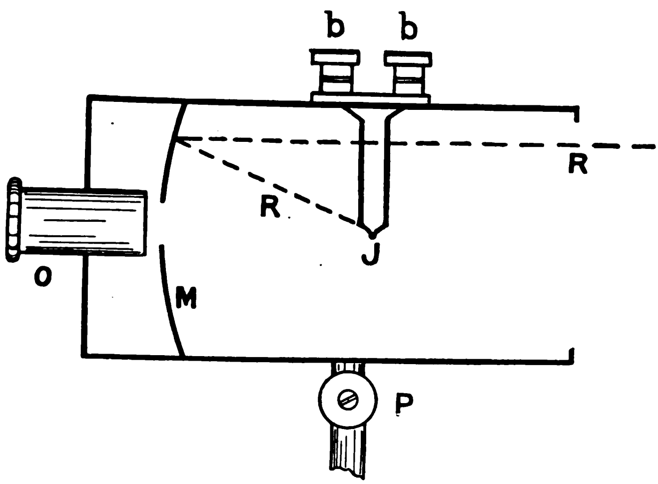


FIG. 95.—Féry radiation pyrometer.

point, so that its temperature depends on the amount of heat, radiated from the object. The thermo-E.M.F. of the junction, and consequently its temperature, is read off in the ordinary way, by means of a galvanometer joined to the two terminals (*b*, *b*).

The law on which the instrument is based was established in 1880 by Stefan, and later corroborated by Boltzmann, and is to the effect that the **heat radiated from a glowing "black body"** is proportional to the fourth power of its absolute

temperature. The observations already made on the subject of "black bodies" apply equally in this case.

For temperatures exceeding 1,500° C. the amount of radiation reaching the thermo-junction is, as a rule, reduced by partially closing the open end of the tube. Since an image of the heated body is focussed on to the thermo-junction, it is clear that, except for absorption by the atmosphere, the only effect of varying the distance between them is to increase or decrease the size of the image. Hence, so long as the image overlaps the junction, the reading of the instrument is independent of the distance. This is found to be correct even over such a wide range as from 3 ft. to 60 ft.

Recording Pyrometers.

Nearly all the pyrometers already described can be arranged to record continuously on a paper chart. The E.M.F.'s or currents to be dealt with are, however, in most cases extremely small, so that especially sensitive instruments are necessary. For this reason an inkless recorder (p. 150) or the Callendar recorder (p. 157) are usually employed.

CURVE-TRACERS AND OSCILLOGRAPHS.

It is important, for many purposes, to be able to determine the shape of a current or potential wave. The wave may either be a recurring one, as in the case of an alternating current circuit, or it may be transitory, as, for example, with the discharge from a condenser. In the first case, either an oscillograph or a point-by-point curve-tracer can be employed, but in the second an oscillograph is essential.

Curve-tracers.

The earliest attempts in this direction were made by M. **Joubert**, who in 1881 succeeded, by means of a

rotating contact-maker, in plotting the wave of E.M.F. of an alternator, and in all modern wave-tracers some modification of the **Joubert method** is employed. Such a device, improved by M. Blondel, is shown diagrammatically in Fig. 96. The disc, *d*, of insulating material, is fixed to the spindle of the alternator whose wave-form is to be traced. The disc carries a metal drum, against which rests the spring brush b_1, and it also carries a metal arm (*a*), which makes contact successively with b_2 and b_3 as the disc revolves. Thus, the condenser *C* (usually of about $\frac{1}{3}$ m.f. in capacity) is placed in contact first with b_2 and then with b_3. If the terminals T_1 and T_2 are connected across the source of E.M.F. to be investigated, the condenser is first charged up to this instantaneous potential, and then discharged through the galvanometer *G*; and the discharges take place so rapidly that it gives a permanent deflection. It is preferable to make the contact occur once every cycle, which can be done by causing the disc *D* to make one revolution per cycle, or by providing it with an additional contact arm (*a*) for every pair of poles on the alternator.

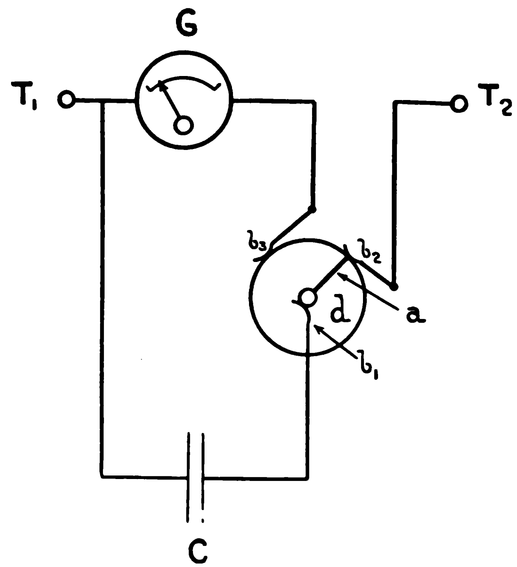


FIG. 96.—Wave-tracing contact-maker.

If the brushes, b_2 and b_3, are moved round through a small

angle, the deflection on the galvanometer will correspond to the instantaneous potential difference at some other point on the curve, and in this way the entire wave can be traced. M. Blondel moved on the contact by a clockwork mechanism, which also drove forward a band of sensitised paper, on which fell a spot of light from the mirror of the galvanometer G, the curve being thereby traced quite automatically.

M. **Hospitalier**, in his "**ondographe**," employs the same principle, except that he moves the contacts forward by gearing them to the disc. This arrangement has the advantage of making the records exactly repeatable, so that curves of current and E.M.F., for example, can be taken one after the other, and subsequently superposed. The working forces have also been so far increased as to make it possible to employ a pen to record the curve.

In many cases it is inconvenient to drive the disc from the alternator itself, and a **synchronous motor** is then employed. The angular velocity throughout the revolution must, however, be perfectly even, or the curves will be distorted, and for this reason it is preferable, when possible, to couple the disc to the alternator direct.

Oscillographs.

The principle on which all oscillographs are based is that of a galvanometer, through which an alternating current is sent, and which tends to follow the pulsations of the current. In most cases the **inertia** of the moving parts is too great to allow of rapid reversals being followed, but if the free period of vibration of the galvanometer (that is to say, the time taken to make a complete swing when mechanically deflected) is reduced to, say, $\frac{1}{50}$ of the periodic time of the current to be investigated, the instrument will faithfully follow its variations. It is further essential that the movement should be extremely well damped, so as to prevent "hunting."

Modern oscillographs are of three types:—

(1) Moving-iron;

(2) Moving-coil;

(3) Hot-wire.

The **Moving-iron pattern**, introduced by M. **Blondel**,[1] has a permanent magnet field, in which is stretched a thin strip of steel under considerable tension. This strip lies with its width along the lines of force. Two coils in series, carrying the current to be investigated, are so placed as to produce a field at right angles to the permanent magnet field. The strip, tending to set itself along the resultant field, is twisted more or less one way or the other, according to the strength and direction of the current.

The momentum of the moving system is so small, compared with the control, that its **free period of vibration** may be something like $\frac{1}{30,000}$ second. The strip has a minute mirror attached to its centre, and is critically damped (see p. 36) by being fitted into a glass tube, filled with castor oil. It is found that, with such an arrangement, so long as the frequency of the current does not exceed 2 per cent. or 3 per cent. of that of the strip, the mirror will accurately follow the wave-form, however distorted.

When the phenomena to be studied are transitory, the only method of recording them is by means of a **photographic plate,** which can be allowed to fall in the path of a ray of light reflected from the vibrating mirror.

A more convenient arrangement, **where the curves repeat themselves** continuously, as is usually the case with an alternating current, is that shown in Fig. 97. An arc lamp, or other intense source of light (A), sends a beam through the lens L, on to the oscillograph mirror M_1, which is supposed to vibrate about an axis parallel to the plane of the page. The vibrating ray of light strikes the mirror M_2,

[1] *Comptes Rendus*, vol. cxvi., p. 502.

and is reflected on to the ground-glass receiving screen S, where it traces a straight line of light, perpendicular to the plane of the page. If the mirror M_2 be oscillated about an axis perpendicular to the page, the straight line will develop into a number of curves, which, owing to persistence of vision, appear to cross and recross one another. If, however, the oscillations of the mirror M_2 are made to synchronise with those of the oscillograph mirror (M_1), the curves will lie accurately on the top of each other. In order that the resultant curve may truly represent the wave-form, it is essential that the angular velocity of the mirror M_2 should be

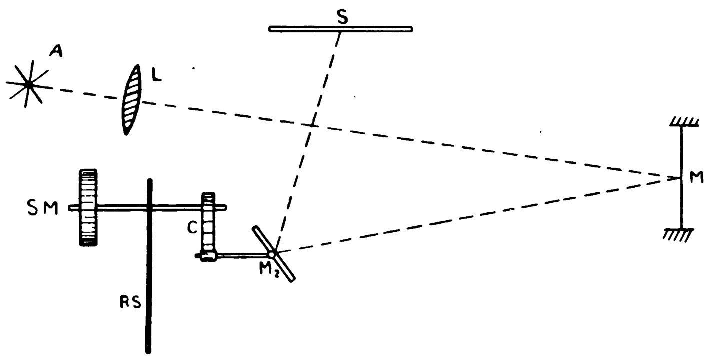


FIG. 97.—Oscillograph wave tracer.

constant throughout its travel. This is secured by means of a specially shaped cam (C), driven by a synchronous motor, SM, and against which rests an arm, attached to the pivoted mirror. At the end of its stroke, the mirror returns to its original position, as rapidly as possible, by falling down a steep part of the cam. To avoid the curve on the screen being thereby disturbed, a rotating shutter (RS), attached to the motor spindle, is so set that it cuts off the light during the return of the mirror by coming between L and M_1. With this arrangement, the period of extinction is so short that hardly a flicker is noticeable on the screen.

Various forms of **synchronous motor** are in use for actuating the mirror and shutter, the simplest consisting of a two or four-pole stator, within which rotates an H or double-H armature. It can be started up by means of a winding and commutator, and when once in step, the winding may be cut out, and the armature will continue to run as an "attracted iron" motor.

For many purposes, it is instructive to be able to **record two quantities simultaneously**, for example, amperes and

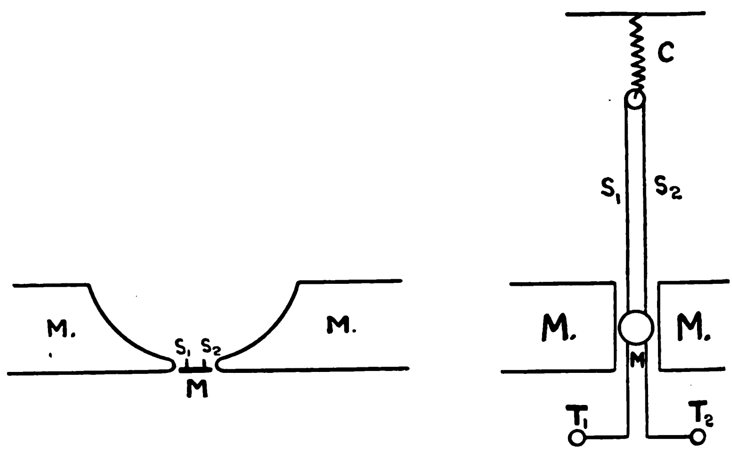


FIG. 98.—Duddell oscillograph.

volts. To this end oscillographs are, as a rule, made double, that is to say, two air-gaps are provided, each having its strip and mirror. One winding carries a current proportional to the pressure, and the other one proportional to the current.

The **moving-coil principle** was first applied to oscillographs by M. Blondel, but its successful development is due almost entirely to Mr. **Duddell.** The principle of action will be gathered from Fig. 98. In the narrow air-gap of a permanent, or electro-magnet (M), a strip of phosphor-bronze is

stretched over a pulley. The current to be investigated passes in at T_1, up S_1, down S_2, and out at T_2. Thus one strip is urged forward, and the other back, and the mirror M, attached to their centres, is turned through a small angle. The tension of the spring C exerts a controlling force, and, the angular deflection being extremely small, is practically proportional to the current flowing. The motion is damped by immersing the strips in a bath of oil.

This construction possesses the advantage, compared with the moving-iron type, of quite negligible **self-induction**, so that it can be shunted for use as an ammeter. The indications can be observed or recorded in the way shown in Fig. 97, and, as a rule, two systems are employed, one for volts and the other for amperes.

The latest form of oscillograph is the **hot-wire type** due to Mr. J. T. **Irwin.**[1] At first sight it would appear that, owing to its sluggishness of action, a hot-wire instrument was singularly ill adapted to the purpose. Mr. Irwin has shown, however, that when proper precautions are taken, a very simple and efficient oscillograph can be so constructed. The first essential is a hot-wire galvanometer, giving a deflection proportional to the current flowing through it, and in a direction depending on that of the current. The construction of such a galvanometer is shown in Fig. 99.

The current from the battery B flows up w_1 and w_2 and down R_1 and R_2, while that to be measured flows as shown by the arrows. Hence the wire w_1 carries a current proportional to the sum of the two currents, and w_2 one proportional to their difference, so that the extensions will be proportional to the squares of these quantities. Thus, if that proportion of the current to be measured which flows in w_1 and w_2 is represented by C_1, and that due to B in each of the wires by C_2, the heating, and consequently the extension of w_1, will be

[1] Paper read before Inst. E.E., May 23rd, 1907.

proportional to $(C_1 + C_2)^2$, and that of w_2 to $(C_1 - C_2)^2$. sequently the difference in the extensions of w_1 and proportional to $(C_1 + C_2)^2 - (C_1 - C_2)^2$, that is, to $4\ C_1$ (

Thus if C_2 is constant the difference will be propor to C_1, and will change sign with it. It is assumed th and R_2 are equal in resistance, as are also w_1 and w_2, a these resistances remain constant, the difference in the e sions will be proportional to the current to be meas Hence it follows that, if some means can be found for m

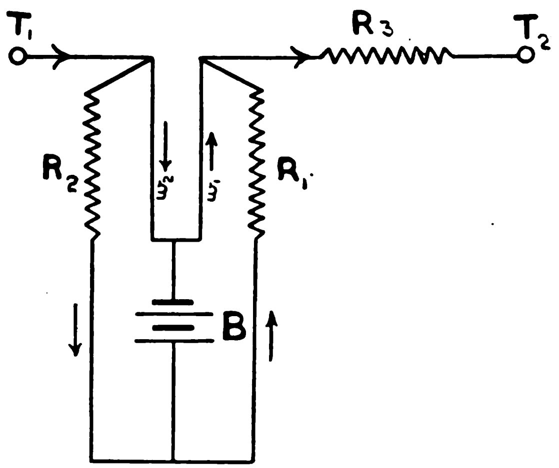


FIG. 99.—Irwin hot-wire oscillograph.

the deflection proportional to the difference in the exter of w_1 and w_2, the required polarised galvanometer, g deflections proportional to the main current, will be avail

Fig. 100 indicates one method of doing this. The strips w_1 and w_2 are fixed at both ends and pass over insu pulleys (p_1, p_2), being kept taut by means of the spring S. middle point of the front half of strip w_1 is tied acro (but insulated from) the back half of w_2, while the back h w_1 is similarly attached to the front half of w_2, as shown a

onsequently, if w_1 expands more than w_2, the points marked 1, w_1, in III. are drawn nearer together, and the points w_2, w_2, are ulled further apart, so that the mirror M, attached to the iiddle points of the front halves of the two strips, is eflected. The amount depends on the difference of temperature

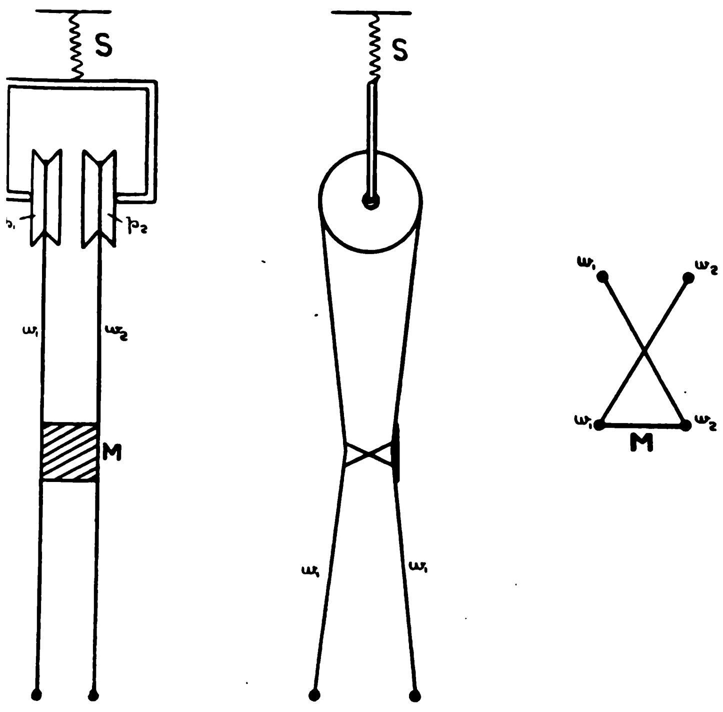


FIG. 100.—Arrangement of wires of Irwin's hot-wire oscillograph.

tween w_1 and w_2, that is, on the current to be measured. stead of being cross-tied, the strips themselves are in ıctice linked over one another, which considerably simplifies ɜ construction.

Suppose, now, that the instrument is connected in series

with a high non-inductive resistance, R_3, and that the terminals T_1 and T_2 have a voltage applied to them. The current flowing, and with it the deflection, will be proportional to the voltage, and will follow accurately any change in its value, provided this change is sufficiently slow to allow the wires to attain their final steady temperature after each change.

The considerations governing the time required for this are as follows: A wire carrying a current will go on getting hotter and hotter, until the heat radiated from its surface is exactly equal to the heat generated in it, and since the heat radiated increases with the temperature, a stable point is ultimately reached. Moreover, if the radiation is increased (which can be done either by increasing the cooling surface or by immersion in oil) the lower will be the temperature at which this equilibrium is established.

To raise the wire to this particular temperature, a certain quantity of heat is required, depending on the size of the wire and on its material.[1] This heat is supplied by the current, and a given current will impart a given number of heat units to the wire *per second*. Suppose that, in a certain case, the final steady temperature corresponding to C_1 amperes is 100°, and that the current is suddenly increased to C_2 amperes, which corresponds, let it be further supposed, to a steady temperature of 110°. Then the wire has to be raised from 100° to 110° by means of a current of C_2 amperes, and this will occupy a certain definite time. Consequently, unless the current alters comparatively slowly, the deflection will not correctly follow the changes, but will lag behind. It is found

[1] To raise the temperature of m grammes of a substance by t° C. (neglecting radiation) requires $m\,s\,t$ gramme-calories, where s is practically constant for a given material and is known as its "specific heat." For water $s = 1$; aluminium $s = \cdot 21$; iron $s = \cdot 11$; copper $s = \cdot 095$; platinum $s = \cdot 03$. To reduce the temperature by t° C. requires the abstraction, by radiation or otherwise, of an equal amount of heat.

practice, that when all precautions as to cooling, etc., have en taken, such an instrument is incapable of accurately llowing the wave-form of an alternating current having a equency greater than, say, 5 cycles per second.

Mr. Irwin, however, has devised an ingenious method of

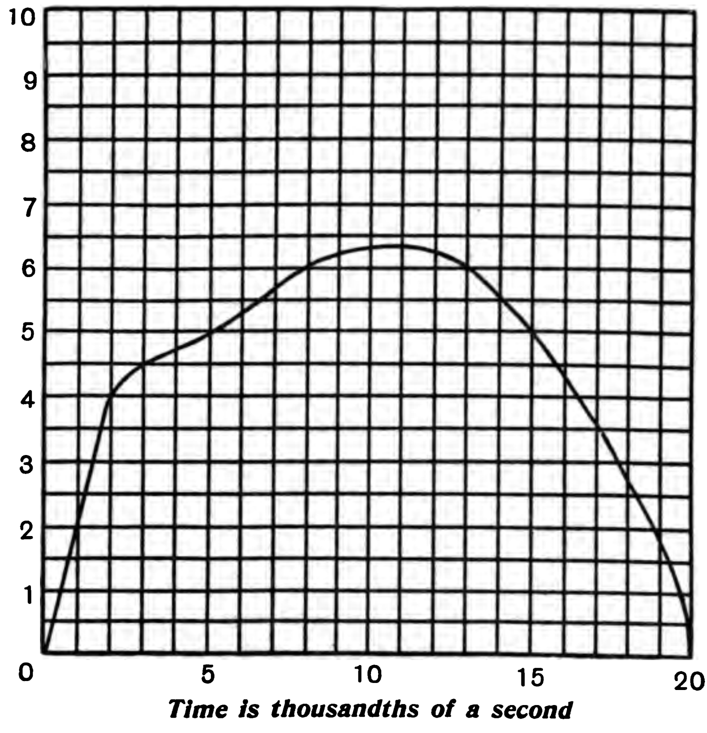


FIG. 101.—A typical half wave.

ccelerating the heating. Fig. 101 shows a wave-form uch as an oscillograph might be required to follow. It will be een that the change in deflection (*i.e.*, in temperature) has to ake place much more rapidly at some points than at others. 'or example, the change from 2 to 4 amperes takes place in ne thousandth of a second, whereas, during the next

thousandth there is only a change from 4 to 4·5 amperes, and at the top the current remains practically stationary for two thousandths of a second. Now, the only way of accelerating the heating of the wire is by increasing the current flowing through it, since, as has been seen, a given rise of temperature entails the absorption of a fixed quantity of heat by the wire.[1]

Thus, what is wanted is some means of making the current which flows through the wire at any instant proportional to the rapidity with which the change of temperature should take

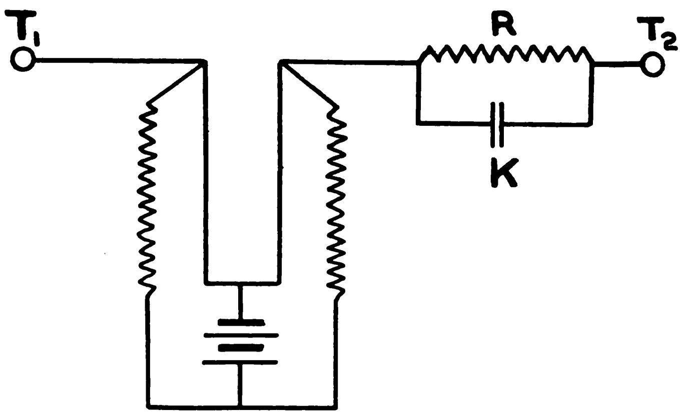


FIG. 102.—Irwin hot-wire oscillograph.

place. That is to say, the current should be proportional to the rate at which the potential difference between T_1 and T_2 (Fig. 99) is changing. The current which flows into a condenser provides precisely this, since it is a maximum when the rate of change is a maximum, and zero when the rate of change is zero.

[1] The rate of heating being proportional to the current flowing through the instrument, the net quantity of heat is proportional to amperes × time; so that, to decrease the one, the other must be proportionally increased.

Hence it follows that, neglecting radiation, if the resistance R_3 is replaced by a condenser, the deflection of the mirror will accurately follow the wave of potential difference.

In an actual instrument, however, radiation is by no means negligible, and a compromise must be made, so that in practice the condenser K is shunted by a resistance, R, as shown in Fig. 102, the ratio of capacity to resistance being so adjusted as to eliminate sluggishness.

The instrument can be arranged **to measure current** in a similar way; the strips being in this case shunted by an inductive resistance, since the potential difference at its terminals will be proportional to the rate of change of *current*. By an arrangement similar to that of Mr. Field (see p. 115), an oscillograph can moreover be arranged to indicate **power**.

It has been assumed in the foregoing discussion that the **free time** of swing is negligibly small compared with the frequency of the current under observation, a condition which is easily fulfilled in practice.

FAULT AND LEAKAGE DETECTORS.

These instruments may be required for either of two purposes :—

(1) To indicate the existence of a fault, and possibly to determine its magnitude;

(2) To locate it.

The indication may be required while the mains are alive, but the localisation is almost invariably left till the current can be cut off. The subject is a very special one, and has been dealt with in many publications, so that only an outline of the methods in use, can be given here.

The **detection of a fault** on dead mains is usually carried out by the **Wheatstone bridge** (p. 39), or one of the **insulation test-sets** (p. 47) already described. Moreover,

as shown in Fig. 18, the bridge method can be used to detect faults during working. Within the last few years, however, considerable attention has been given to the subject of leakage detection on live mains, largely owing to the fact that the new **Home Office rules,** for the use of **electricity in coal mines,** stipulate that some form of indicator is to be installed which will continuously indicate the state of the insulation.

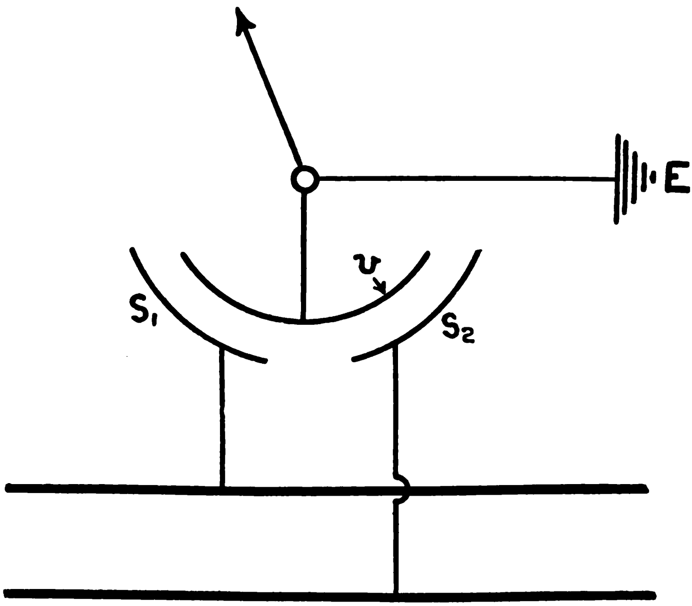


FIG. 103.—Electrostatic leakage indicator for single-phase systems.

For **high tension single-phase insulated systems,** the usual method is to connect an **electrostatic voltmeter** between each main and the earth.[1] If the insulation of both

[1] It is not advisable on high-tension systems to connect a comparatively low resistance to earth, owing to the danger of shocks being obtained between the *other* main and the earth. For this reason transformers connected to earth are not to be recommended, although leakage indicators have been designed involving their use.

mains is approximately the same, each voltmeter will indicate half the line voltage. Should one read lower than the other, it indicates that the insulation of the main to which it is connected is lower than that of the other. The readings are, in fact, inversely proportional to the insulation resistance of the two mains. If the line voltage is steady, one voltmeter is sufficient, since the other voltage can always be obtained by deducting the voltmeter reading from the line voltage. In this case it is best to connect the instrument to the main which has the lower insulation.

The two instruments can be conveniently combined into one, as shown diagrammatically in Fig. 103. The pivoted vane (v) is connected to earth, while the fixed sectors S_1 and S_2 are connected, one to each of the two mains. The pointer stands normally at the centre of the scale, being equally attracted by S_1 and S_2. Should the insulations be unequal, however, v will be drawn over to one side or the other, and the pointer will indicate the ratio between the two voltages, that is to say, the ratio of the insulation resistances of the two mains.

Instead of voltmeters, **vacuum tubes** are sometimes used, and afford a rough indication of the state of the insulation. For three-phase insulated systems, three electrostatic voltmeters or vacuum tubes are used, each connected between one of the mains and the earth.

For **low-tension insulated systems,** whether direct or alternating current, the same arrangements are applicable; but in this case electrostatic instruments are not essential, and the choice of methods is wider. For **two-wire systems,** a voltmeter, connected as shown in Fig. 104, can be used. A resistance, r r, is joined across the mains, and from its middle point a voltmeter ($V\ M$) is connected to earth. If the insulations are equal, no deflection is produced, but if they are unequal, a current flows through the instrument.

On direct current systems a central-zero moving-coil instrument can be used, and it will be deflected to one side or the other, according to the relative states of the insulation.

Besides the continuous indication of relative insulation, such a voltmeter, connected first to one main and then the other, can be used to determine the *actual* insulation of each. The working pressure (V) is first measured, and the voltmeter (of resistance R) then connected successively between each main and the earth, readings v_1 and v_2 being obtained. The respective insulations of the two mains are then:—

$$\left.\begin{aligned} I_1 &= \frac{R\,(V - v_1 - v_2)}{v_2} \\ I_2 &= \frac{R\,(V - v_1 - v_2)}{v_1}. \end{aligned}\right\}$$

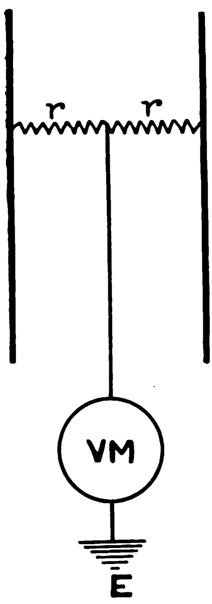


FIG. 104.—Leakage indicator for two-wire system.

In the case of **direct current** installations, this method gives extremely accurate results, but on **alternating current** circuits, **capacity effects** disturb the readings to such an extent that they can only be regarded as relative.[1] For direct current circuits, in order to save calculation, tables are often worked out from which the value of I_1 and I_2 can be read off, as also of the leakage current flowing from main to main through the earth. This latter is frequently of importance; it is stipulated for example in the new coal-mining regulations that it shall not exceed $\frac{1}{1000}$ of the normal full-load current.

[1] Dr. J. Sahulka in the *Elektrotechnische Zeitschrift* describes an elaborate method of eliminating capacity effects, but it is hardly likely to be largely used in practice. See abstract in *Electrician*, vol. lix., p. 999 (October 4th, 1907).

In the case of **earthed systems** (*e.g.*, three-wire with earthed middle wire, or three-phase with earthed neutral point) the methods so far given, and depending on a varying potential difference between mains and earth, are inapplicable. Moreover, no thoroughly satisfactory method of continuous indication for such systems has so far been devised. The most usual consists in connecting an **ammeter in the earth circuit**, that is to say, between the earth plate and the system. If the insulation is perfect, no current will flow, but, if any main develops a leak, the leakage current will flow through the ammeter. In **direct current systems** the direction of the current indicates on which of the mains the fault has occurred.

In order to detect slight faults, the ammeter should be a low-reading one, say, up to 1 ampere, and consequently some means must be adopted for protecting it from the heavy current, which will flow in the case of a bad earth. Two methods are available. In one of them an **automatic switch short-circuits the instrument** so soon as the current exceeds a certain value, and in the other a **resistance sufficient to cut down the current** to a safe value, even in the event of a dead earth, is cut into circuit by an automatic switch. The second method has the further advantage that the supply can be continued, however bad the fault on one of the mains; but it must be borne in mind that the pressure to earth of the other mains is thereby raised.

The **usefulness of the earth ammeter arrangement is limited** by the fact that the ammeter only carries the *difference* between leakages, and, consequently, a decreasing deflection may mean either that one main is improving, or that another is getting worse. Moreover, a fault on the middle wire of a three-wire system will shunt the ammeter and thus decrease its readings.

The **only really satisfactory method** to adopt is to

temporarily **open the earth circuit** and then to treat the system as an insulated one. For example, the combined insulation resistance of a three-wire system can be obtained by taking voltmeter readings (v_1 and v_3) between each of the outers and the earth. Then, if V is the voltage between the outers, and R the resistance of the voltmeter :—

$$I = R\left(\frac{V}{v_1 + v_3} - 1\right),$$

$$\text{where } \frac{1}{I} = \frac{1}{I_1} + \frac{1}{I_2} + \frac{1}{I_3}.$$

The methods given are those most widely used, but besides these many others have been suggested from time to time. For example, in the case of **alternating current** insulated systems, a **direct current can be superposed** by connecting a battery in series with sensitive moving-coil ammeter between earth and one or other of the mains. The insulation of the system is given by $\frac{\text{battery volts}}{\text{amperes flowing}}$, and the test can be made during working.

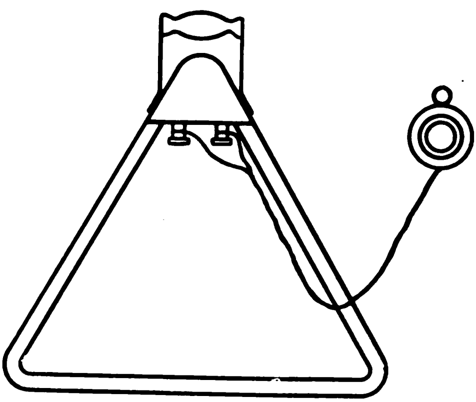


FIG. 105.—Search-coil for fault localisation.

The **localisation of a fault** is, as a rule, carried out by one of three methods :—

(1) Induction method ;
(2) Loop method ;
(3) Fall of potential method.

The **induction method** consists in sending an alternating or interrupted direct current of some 10 amperes through the faulty cable to earth. A search-coil, connected to a telephone receiver, is carried along the street, parallel to the faulty main, and when the fault has been reached the buzzing in the telephone suddenly ceases, or nearly so, owing to the fact that the main beyond the fault does not carry any current.

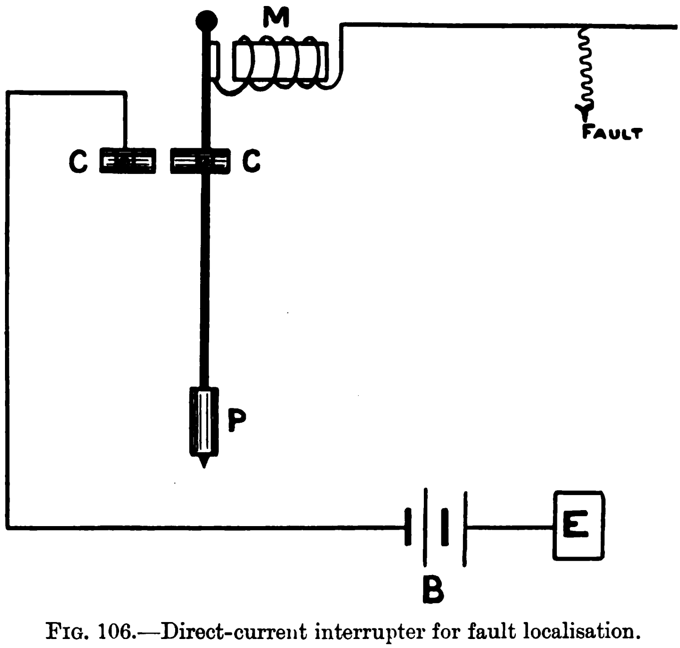


FIG. 106.—Direct-current interrupter for fault localisation.

A convenient form of coil is shown in Fig. 105, and is preferably of such a size that, when carried in the hand, the lower edge, which is held parallel to the main, is a few inches above the ground. In an **alternating station**, the supply current may be employed, but it is more satisfactory to use an **interrupted direct current** of low frequency (say 10 to 20 cycles per second), since the note due to this current can

then be easily distinguished from that due to neighbouring cables carrying alternating currents.

A **form of interrupter** (that of Messrs. Everett, Edgcumbe & Co.) is shown in Fig. 106. The principle is that of an electric trembler, an impulse being given to the pendulum P by the coil M, which is energised by the current flowing, so soon as the carbon contacts C C come together. The battery B has one pole earthed, and the current returns, as shown, through the fault in the cable. The contacts C C, being of carbon, a high voltage source of current can be employed if desired, such as an exciter, or, in a continuous station, one of the

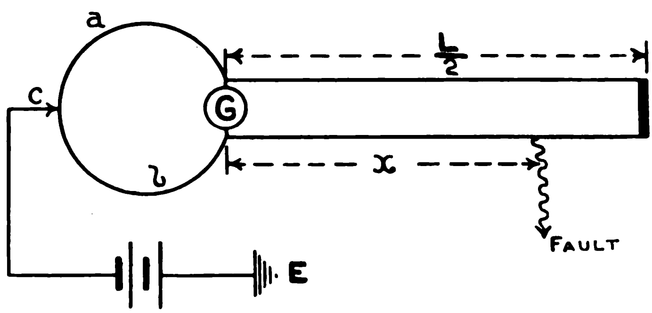


FIG. 107.—Loop test method.

machines. The adjustment of the current to, say, 10 amperes can be made by means of a regulating resistance, or of a bank of lamps.

The principle of the **loop method** will be gathered from Fig. 107, where the lower cable is supposed to be faulty. The two further ends are joined together, and the near ends connected to the terminals of a slide-wire, a b. The contact C is moved along the wire, until the galvanometer G shows no deflection; then, if L is the length of the looped cable, and x the distance of the fault from the station,

$$\frac{b}{b+a} = \frac{x}{L} \text{ and hence } x = L \times \frac{b}{a+b}.$$

The length of the slide-wire should be as great as possible, and its section ought, theoretically, to be so chosen, as to give a resistance of the same order as that of the looped cable, which is usually fairly low.

Great care is necessary in the making of all **joints**, as otherwise their resistance may be quite appreciable compared with that of the cable. For this reason it is better to increase the resistance of $a + b$, and to make the galvanometer con-

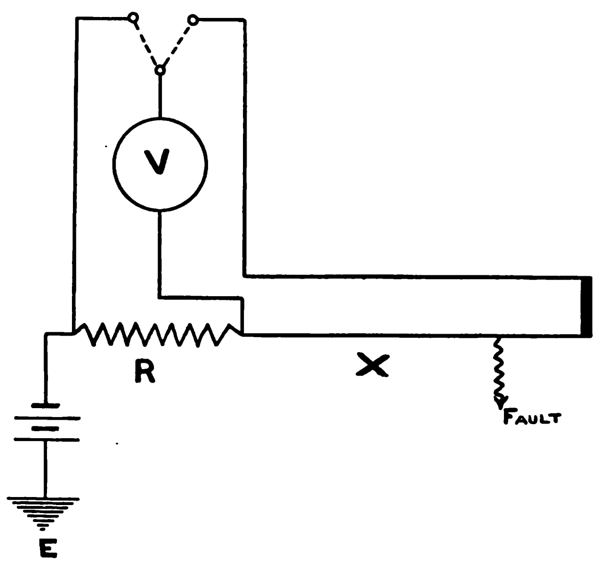


FIG. 108.—Fall of potential method.

nections on to the cable itself, that is to say beyond the joints, so that the resistances of the latter are included in a and b, to which they bear a much smaller proportion than they would to that of the cable. If the mains are not of uniform section throughout their length, L and x are to be taken as the lengths of equivalent section.

The connections for the **fall of potential method** are shown in Fig. 108. The faulty cable, as in the loop test, is joined up

to a sound main, running back to the station. A current is sent through the faulty cable, in series with a known resistance, R, and returns, *viâ* the fault, to earth. The second main acts merely as a pilot-wire, and enables the fall of potential v_1, along the cable to the fault, to be measured on the voltmeter V. A second reading, v_2, is taken over the resistance R, and if X is the resistance of the leaky cable, as far as the fault:—

$$\frac{X}{R} = \frac{v_1}{v_2}.$$

From a knowledge of X the length of the faulty cable can be calculated, provided the resistance per mile is known. Variations of temperature make this value somewhat indeterminate, but it often happens that a pair of sound mains are available, which can be joined together at their further ends, and used to replace R. Then—

$$\frac{\text{distance of fault}}{\text{length of sound cable}} = \frac{v_1}{v_2}.$$

The result will be independent of temperature, but due allowance must be made for any difference there may be in area.

In discussing the above methods, earth faults have throughout been assumed, as being the most common, but the methods outlined can be adapted to faults of almost any kind. The best arrangement must depend entirely upon the circumstances of the case, and no general rules can well be laid down.

RELAYS.

Although, perhaps, hardly to be described as measuring instruments, the importance of relays is becoming so great that they cannot well be passed over. The **function of a relay** is, as a rule, to operate a switch or circuit-breaker in one of the following events:—

(1) An overload,

(2) A failure of supply, or

(3) A reversal of current.

A **simple form** which is applicable to either direct or alternating currents is shown in Fig. 109. The main current, or one proportional to it, is passed through the relay coil *RC* and so soon as it exceeds a certain value the core *A* rises and a local circuit is thereby closed at the contacts *C*. A current then flows from the battery *B* through the tripping coil (*TC*) of the circuit-breaker, and opens it. The core instantly falls back, and the relay is again ready to act.

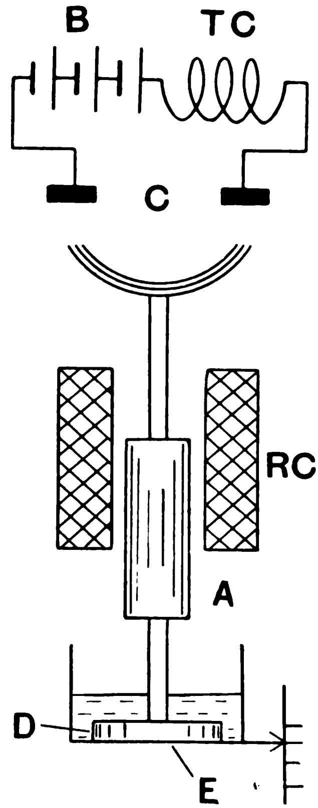


FIG. 109.—Solenoid type overload relay.

In many cases it is not desirable that the breaker should be opened on the occurrence of a momentarily short circuit, particularly if it is not a serious one, and **time-lag devices** are, consequently, often applied. These are designed to retard the action for a certain predetermined time, the length of which depends, preferably, on the extent of the overload. An extremely simple device for the purpose, the **Statter time-lag**, is shown in Fig. 109. A disc, *D*, suspended from the core *A*, rests on the bottom of the little cup *E*, filled with oil. The disc and the bottom of the cup are ground perfectly true, and a considerable force is required to separate them suddenly, although a comparatively small force, applied

for a longer time, is sufficient to do so. Fig. 110 shows the relation existing between the extent of the overload (that is, the pull) and the time which elapses before the relay acts.

A form of **alternating current overload relay** based on

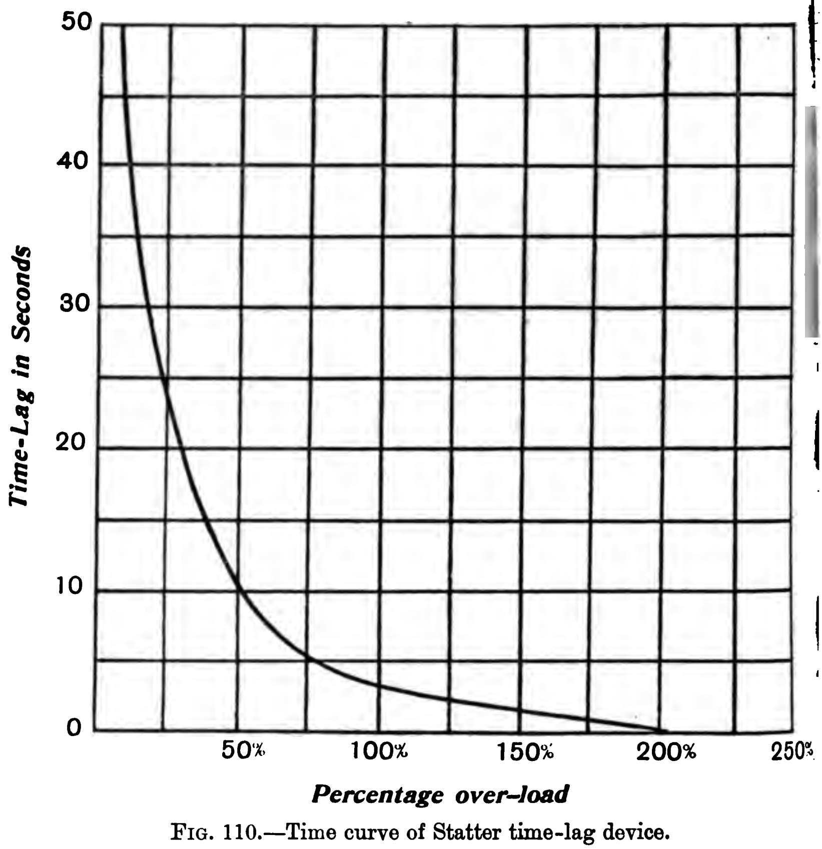


FIG. 110.—Time curve of Statter time-lag device.

the **induction principle** (see p. 81) is shown in Fig. 111. The shaded-pole electro-magnet RC urges the disc D in the direction shown by the arrow, and round the spindle passes a cord (E), kept tight by the counterweight W_2. The pivoted arm carrying the weight W_1 and the contact C is

thereby raised, until the latter closes the circuit. The permanent magnet *PM* induces eddy-currents in the revolving disc, and so retards its motion. Consequently, the heavier the overload, the more rapidly will the disc rotate. The **time-lag** at any particular overload can be varied by adjusting the travel of the contact lever by means of the small screw *S*. Fig. 112 gives a curve connecting time and overload.

A great advantage possessed by this method is that the

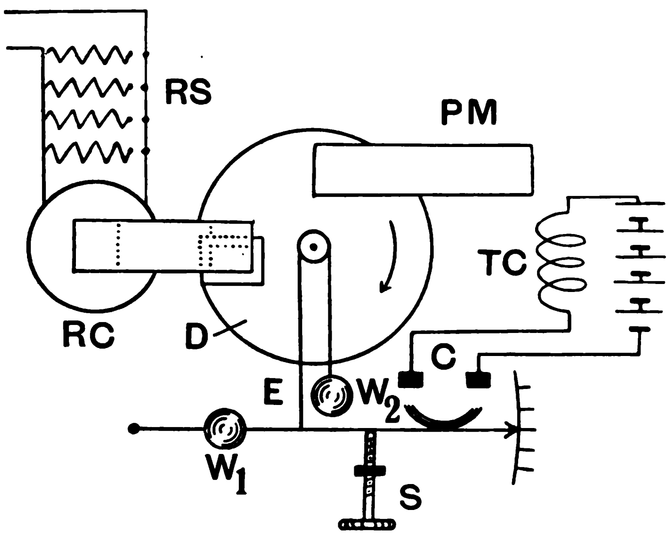


FIG. 111.—Everett-Edgcumbe time-limit overload relay.

curves, for different settings of time-lag, are identical, whereas, when the regulation is done by moving the damping-magnet, as is sometimes the case, all the curves tend to unite at the heavier loads, owing to the fact that the disc reaches a **synchronous speed** which is not exceeded, however great the overload. The curve, Fig. 110, exhibits the common fault of giving no lag at all with overloads exceeding 200 per cent.

This is a matter of considerable importance, since it is essential, in many cases, that the relays should work in a definite and **predetermined order**, no matter what the overload. For example, in the event of an earth on a feeder,

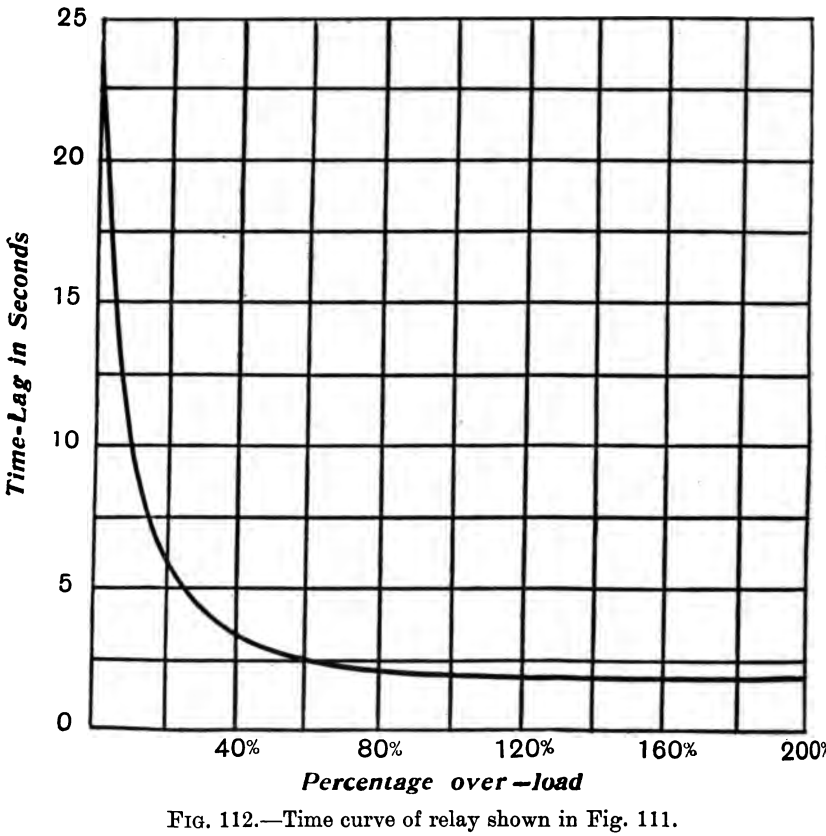


FIG. 112.—Time curve of relay shown in Fig. 111.

the circuit-breaker controlling it must open before that on the generator, otherwise the sound feeders would be shut down as well as the faulty one.

The **current setting** is arranged for by means of adjustable shunts, *RS*, any one of which can be connected in

parallel with RC by means of a plug. By this device the time-lag curves are identical at all settings, whereas, were the regulation effected by varying the control weight, the curves would vary considerably, owing to the saturation of the core.

A **"no voltage," or minimum current relay**, can be constructed on the same lines as either of the above, except that the contacts must be so arranged that, if the current in RC falls below a certain value, the relay circuit is closed and the breaker tripped.

Reverse or discriminating relays for direct current are usually constructed on the moving-coil principle, a contact arm being provided in place of a pointer. The contact is normally held open, but a reversal in the direction of the current closes it.

In the case of alternating currents, some definition of what is meant by a "reverse current" is necessary. When an alternating current generator is feeding 'bus-bars, the current is a forward one, but if the engine slows down, current flows into the generator, and tends to drive it as a motor. In other words, the current, instead of being in the same direction as the voltage, is in the reverse direction.

One of the most obvious devices for operating a relay under these conditions is a **solenoid,** such as that shown in Fig. 109, but having two windings, series and shunt, so arranged as to oppose one another with a forward current, and to assist one another on a reversal. This arrangement possesses the disadvantage, however, that a large forward current will be sufficient to overcome the pressure winding, and actuate the relay. This is most undesirable in the case of a generator relay, since it is just at such times of heavy overload that the generator is most wanted.

Mr. **Leonard Andrews**[1] has overcome this difficulty in the

[1] Inst. E.E., December 13th, 1904.

way shown diagrammatically in Fig. 113. The relay coil *RC* carries two windings, the one left-handed and the other right. Their point of junction is connected to one of the 'bus-bars, and the outer ends to the two extremities of a choking coil (*CC*), the middle point of which is connected to the other 'bus-bar. When so connected, the relay coil ampere-turns

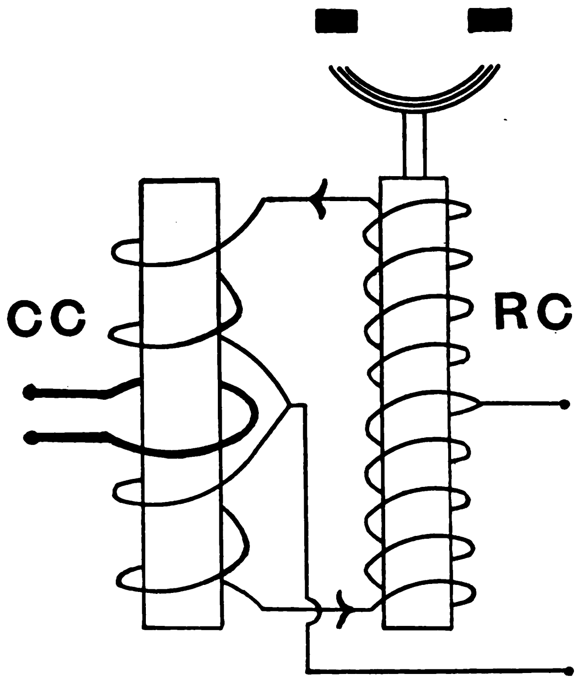


FIG. 113.—Andrews discriminating relay.

cancel out, and the iron core experiences no pull. The choking coil, however, also carries a current winding which, under normal conditions, tends to send a current through the relay coil in the direction shown by the arrow heads, thus strengthening the lower coil, and weakening the upper. By this means, the core is normally held down, but should a reversal of current

take place, the upper coil is strengthened and the flux in the lower coil wiped out, so that if the reverse current exceeds a certain predetermined value, the core will be raised, and the circuit closed. No forward current, however great, can cause the relay to operate, but, on the other hand, any decrease in voltage must be accompanied by an increase of reverse current before the core is raised, though this increase will be less than proportional to the decrease of pressure.

Several reverse relays have been devised on the **wattmeter principle**, one of the most common consisting of an induction instrument, the disc of which actuates the contacts in a manner analogous to that shown in Fig. 111, except that, in place of the current winding *RC*, a wattmeter movement is provided. A forward current holds the contacts open, whereas a reverse current turns the disc in the opposite direction, and so closes them.

If a **time-lag** is desired, a damping magnet can be added as before. But in the case of reverse relays, it is preferable that they should be instantaneous in their action, since they are usually installed with a view to protecting the generators, and, in the event of a breakdown, the sooner the faulty machine is cut out of circuit the better. The only fear is, that the reverse current flowing during a bad attempt at paralleling might possibly open a very sensitively set reverse relay. This disadvantage can be overcome either by giving a very small time-lag, say something under 1 second, or by opening the pressure (or current) circuit of the relay while synchronizing. This may be done either by hand or automatically by means of the synchronizing switch or plugs.

A disadvantage possessed by all wattmeter reverse relays is that their working depends on the reverse watts rather than the reverse current, and since, in the event of a generator breaking down, the 'bus-bar voltage will inevitably fall, the reverse current may reach a considerable value before

the watts are sufficient to actuate the relay. Moreover, event of the field of the generator failing, the phase disj ment between current and voltage is considerable, which fu aggravates the trouble. It is usual, for these reasons, reverse relays to work at 10 per cent. or 15 per cent. c normal forward watts, with the disadvantage, mentioned a of ultra-sensitiveness when synchronizing.

A reverse relay which, practically, gets over this obj

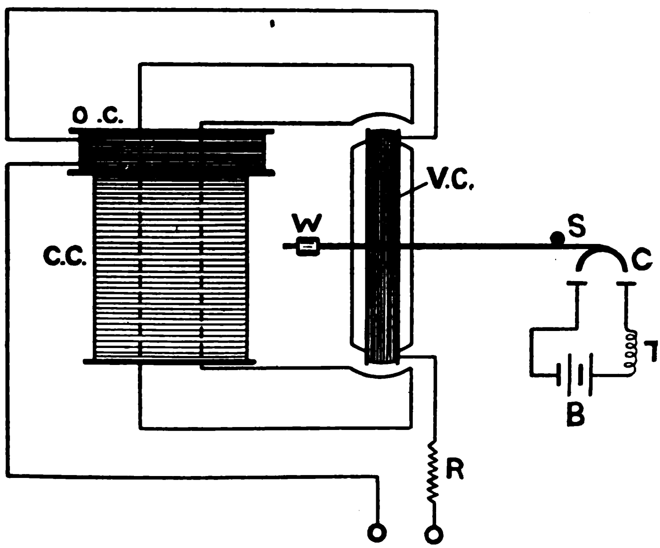


FIG. 114.—Everett-Edgcumbe reverse relay.

is that manufactured by Messrs. Everett, Edgcumbe & Co shown in Fig. 114. It consists of an iron-cored dynamo wattmeter having a current coil (*CC*) and a volt coil (the latter connected through a large non-inductive resis across the mains. In series with *VC* is a coil *OC* so nected as to oppose *CC* when the latter carries a re current. When no current is flowing the contacts are open by *W*, the arm which carries them resting agains

op S. The effect of OC, and of a forward current in CC, is to keep the contacts in this position. When, on the other hand, a gradually increasing reverse current flows through CC it, first of all, neutralises OC, and then overcomes it. Thus the flux in the air-gap is that due to CC minus that due to OC, and so soon as this difference exceeds a certain predetermined value, the control due to W is overcome and the contacts C close.

Without the opposing coil OC the action would depend solely upon the reverse power, and consequently a fall of pressure would entail a proportionately increased current before the relay acted.

With the arrangement shown, however, a fall of voltage means a decrease in the opposing ampere-turns, due to the OC coil and, consequently, an increased flux in the air-gap for a given current in CC, so that the necessary reverse current is much less affected. For example, if, when the relay acts at the normal voltage, the ampere turns of OC amount to 60 per cent. of those in CC, the proportionate currents in CC necessary to actuate the relay at various voltages (assuming the permeability of the core to be constant) are as follows:—

Voltage as percentage of normal.	125	100	75	50	25	10	5
Working current as percentage of that required at normal voltage.	107	100	98·4	110	175	406	800

From the above it will be seen that even if the pressure falls to half its normal value it will only require a current 10 per cent. greater than the normal to actuate the relay, instead of double the normal, as would be the case with the wattmeter pattern.

Relay **contacts** are usually either of carbon, laminated copper, or mercury. When the working forces are small (as is often the case with reverse relays), or when exceptionally

good contact is required (see below), mercury is essential; but carbon is generally to be preferred.

In some cases the relay closes a direct-current circuit through the tripping coil *TC*, and, as it is most convenient to obtain current for this purpose from an exciter or a lighting circuit, the voltage will probably be at least 100 and more often 200 or even 500. Such being the case, some precautions are necessary as regards **breaking this circuit at the relay contact.**

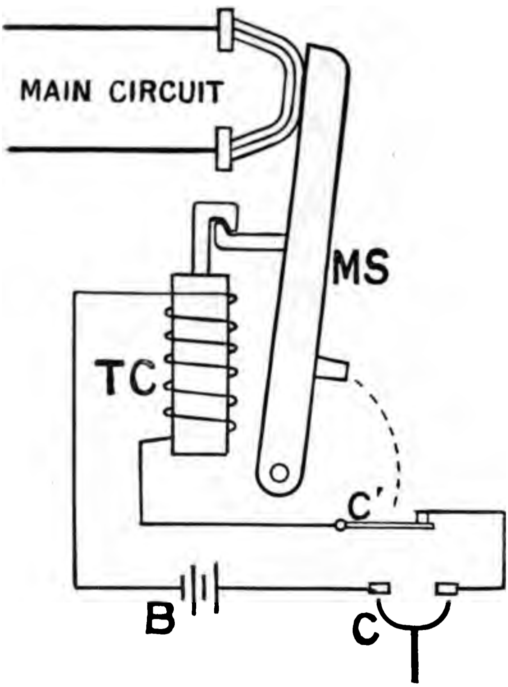


Fig. 115.—Relay connections showing auxiliary breaking switch.

The most satisfactory arrangement is to provide the circuit-breaker, actuated by the relay, with an auxiliary switch in the tripping circuit, which is automatically opened by the falling out of the main switch. By this means the tripping circuit is broken at a point where the arc can be satisfactorily dealt with. Fig. 115 shows the connections for such a circuit. The tripping coil *TC* releases the main switch *MS* which, in falling, opens the tripping circuit at *C′*. So soon as *MS* is reset, the switch at *C′* automatically closes, and the relay is

again ready for action. When this arrangement is inconvenient, as for example, in some remote control-boards, the coil *TC* can be shunted by a non-inductive resistance which forms a return path, in parallel with *C*, when the circuit is broken. Of the two arrangements, however, the former is much to be preferred.

In many cases an auxiliary source of current is not available, and the **current transformer which works the relay is employed**, as shown in Fig. 116. The secondary of the current transformer (*CT*) is connected in series with the tripping coil (*TC*) of the circuit - breaker and the relay coil (*RC*). The former is normally short-circuited at the contact *C*, but directly the relay acts the secondary current flows through *TC* and trips the switch. Such a device is not applicable to reverse relays, since the current at which they are set to trip is usually too small to successfully work the circuit-breaker. Since the satisfactory operation of a relay connected as in Fig. 116 depends on the resistance of *C* being negligibly small, mercury contacts are, as a rule, employed.

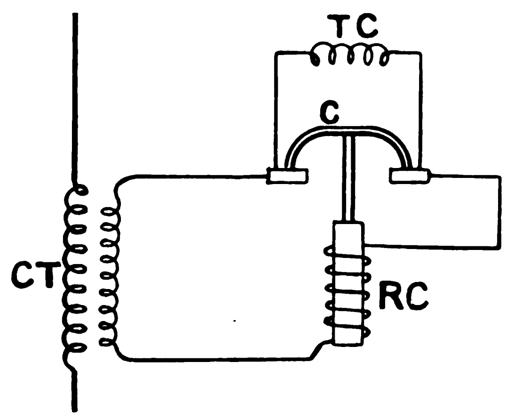


FIG. 116.—Use of a current transformer for operating a relay.

It is not satisfactory to use **potential transformers** to actuate relays, since, on the occurrence of a bad fault, the pressure may very possibly fall too low to work the tripping coil.

HIGH TENSION LIGHTNING ARRESTERS AND SURGE GAPS.

The nomenclature of this subject is in a somewhat chaotic state, the word "**Lightning**" being generally understood, in this connection, to cover all phenomena causing abnormal rises of pressure in a circuit. The word "**Static,**" moreover, is often used in the same sense, although most abnormal rises of pressure are due to oscillatory discharges.

It is necessary to distinguish between—

(1) **Static charges** proper, due to atmospheric conditions.

(2) **Surges,** due to sudden changes of current, which may be brought about, for example, by the opening or closing of a circuit, either in the ordinary course of working, or owing to a short circuit or earth.

(3) **Currents induced** in conductors by a lightning discharge in their neighbourhood.

(4) **Direct lightning strokes.**

Troubles 1, 3 and 4 are practically confined to overhead lines, while 2 is most common on systems of underground mains, or on those consisting partly of underground and partly of overhead conductors.

Static charges may be caused by a fall of snow or by a sudden cooling of the atmosphere, at nightfall for example, or even by rain or fog. Again, the presence of a charged cloud in the neighbourhood of a line induces a charge in it. Suppose, for example, that the cloud is positively charged, the earth will thereby be negatively charged, and the line being insulated, will remain nearly at its former potential, and will consequently be negative to the earth. This difference of potential may become so great as to break down the insulation to earth at some point, or, if unable to do so, the charge will gradually leak away over the insulators.

On the cloud passing away, or discharging to earth, the latter

resumes its original potential, and the line is positively charged relatively to it, possibly to such an extent as to again break down.

Surges are caused by any violent and sudden change in current, or pressure, on a line. For example, if a circuit is suddenly closed, a wave rushes along the line with a velocity of the same order as that of light. At the further end it rises to double the original voltage, and is reflected back to the starting end, and so on, the pressure gradually falling until all the energy has been dissipated in heat or by leakage. The phenomenon is much the same as that which occurs in a trough of water: a wave started at one end travels to the further end, where it rises to twice its original height and is reflected to the point it started from, and continues to travel up and down the trough, the height gradually growing less and less. Such abnormal rises of pressure are not caused merely by sudden increases of current; the effect is the same if the circuit is suddenly broken, say by the blowing of a fuse. The frequency of such surges depends upon the length of the line, and also upon its capacity and self-induction, but it is usually something like 1,000 to 2,000 cycles per second.[1]

If, instead of the line ending abruptly, as has been assumed, it is connected at the further end to another line of much smaller capacity (for example, an underground cable being joined to an overhead conductor), the pressure will still rise to something like double, and this increased pressure will surge up and down the overhead line, again rising to nearly double at the further end, and thus giving a pressure equal to almost four times the normal. It will readily be seen, therefore, that on an extended system such a surge may have very disastrous results.

Fortunately, the frequency, which depends upon the length, capacity and self-induction of the line,[1] is comparatively high,

[1] The frequency in cycles per second $= \dfrac{1}{2\pi\sqrt{L\,C}}$; where L is the self-induction of the line in henrys and C its capacity in farads.

so that **resonance** with the normal supply frequently is improbable. With long cables, however, particularly if they possess considerable capacity, there is a chance of resonance occurring with some of the higher harmonics in the case of a generator, giving a very distorted wave.

A **lightning discharge in the neighbourhood of** an overhead line, being oscillatory, induces in it an extremely high voltage at a frequency of something like 500,000 or 1,000,000 cycles per second. This charge either jumps to earth, or, if unable to do so, oscillates backwards and forwards until dissipated.

The danger in all four cases is two-fold. Firstly, much damage may be done should the charge rush to earth through some weak spot in the insulation, either of the plant or the transmission line, and, secondly, due to a so-called "**concentration of potential**" on the end turns of the windings of machinery, when an increased pressure is suddenly thrown on them. This concentration is due to the fact that the winding and its iron core, for example, form the two plates of a condenser. The turns become successively charged up, the inner ones only reaching their full potential after an interval of time sufficient to charge up those nearer the line. During this time, nearly the full pressure exists between the first few turns, so that the voltage per turn may reach ten or more times its normal value.

To protect machines from both these troubles, it is usual to place "**choking**" coils, consisting of some ten or more turns of bare copper, in each feeder at the point where it leaves the station. The self-induction of these "**kicking coils,**" as they are sometimes called, is insufficient to produce any appreciable choking effect on the line current, at its moderate frequency, but to surges, and still more to lightning discharges, owing to their enormous frequency, such choking coils are almost impassable. It is still essential, however,

to relieve the line from the abnormal pressure, and for this purpose lightning arresters are used.

In the **design of arresters** it is essential to distinguish carefully between the four sources of disturbance, and it is a failure to do so that has led to many unsatisfactory results in the past.

As regards **direct lightning strokes**, it must, unfortunately, be admitted that no device so far introduced can be relied upon to deal with them, owing to their suddenness, and the fact that the discharge usually rushes to earth through the nearest pole. Such direct strokes are however rare.

Of the other three, the easiest to deal with is the **static charge**, since it, as a rule, accumulates somewhat slowly, and can be led to earth either through a high resistance, or better still, a choking coil connected between the line and the earth, or else over one of the ordinary arresters described below. A great advantage possessed by the choking coil as compared with the non-inductive resistance, for this purpose is, that while the alternating current leakage to earth can be kept quite small, the ohmic resistance is low, so that uni-directional static charges are rapidly led to earth.

In some water-power plants, so-called "**water-jet arresters**" are used, consisting either of a jet of water playing on to a conductor connected to the lines, or a column of water contained in an insulating pipe, and connected at one end to the earth, and at the other to the line. These arresters must not be looked upon, however, as any real protection against lightning, since their resistance is too high, but they afford almost perfect protection against static charges. The chief objections to their use are that they constitute a permanent leak, and moreover necessitate a constant supply of running water, even with the column pattern, owing to rapid evaporation.

Surges are usually of comparatively low pressure, say not

more than three times the normal (see p. 201), and the energy to be dealt with is moderate, so that it is not a very difficult matter to cope with them. Nearly all arresters for this purpose (or "surge gaps" as they are often called) consist of either—

(1) **A spark gap alone.**

(2) **A spark gap in series, with a non-inductive solid resistance.**

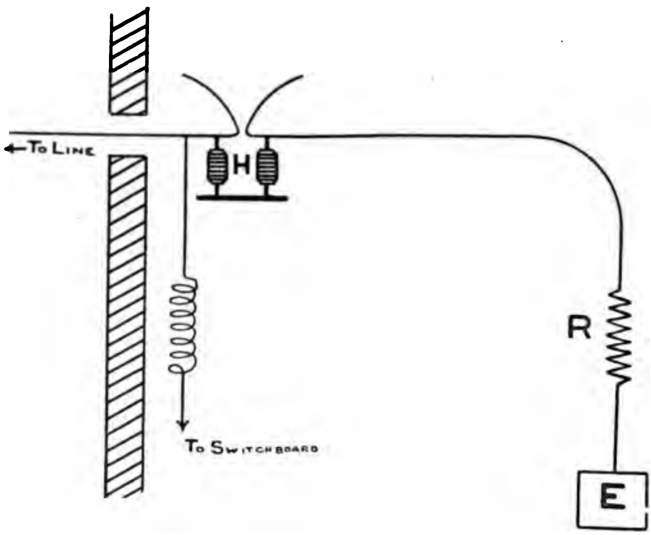


Fig. 117.—Horn lightning arrester and choking coil.

(3) **A spark gap in series with an electrolytic resistance.**

(4) **A condenser.**

A disadvantage of the **simple spark gap** lies in the fact that when once an arc has been started by the surge, the line current is carried over, and may reach such a value that the generator circuit-breakers are opened, or if the arc is satisfactorily broken, either by a horn or magnetic blow out

arrangement, the current interrupted is so great that further serious surges may be produced. It is, therefore, usual to limit the current flowing by inserting a **non-inductive resistance in series** with the spark gap. Fig. 117 shows such an arrangement, where H shows a so-called horn arrester due originally to Siemens, and R a non-inductive resistance, connected to an earth plate at E. The horns are set at such a distance apart that a rise of some 50 per cent. in pressure will cause a spark to pass at the nearest point.[1] The arc once formed, the line current tends to follow, but owing to magnetic repulsion, combined with an upward draught, due to the heated air, the arc is driven towards the wider part of the gap, and rapidly broken. The resistance (R) is so chosen that, at normal voltage, the current which would flow to earth, were the gap short-circuited, amounts to from ½ to 2 amperes.

An objection to the horn arrester is that, if the horns are set close enough to allow of a discharge with a moderate rise of pressure (say 50 per cent.), there is a great chance of an accidental short circuit, due to dust or insects, so that for outdoor use the gaps are, as a rule, set with a very considerable margin of safety. Further, with a heavy discharge, a globule of metal is apt to form on one of the horns, whereby the air gap is much reduced. This has been overcome by Messrs. Lahmeyer, by the **use of carbon on one pole** and copper on the other, with the result that, should a globule form, it burns a corresponding cavity in the carbon on the opposite horn.

Another solution of the problem is that due to **Zapf**, and shown in Fig. 118. The main gap (G_1), in series with a non-inductive resistance (R_1), is set very wide, say for five or six times the line voltage. An auxiliary gap (G_2), connected in series with a high resistance (R_2), is set to act at some 25 per cent. above the line voltage, and so soon as it sparks, the air in the neighbourhood is ionised and enables the gap G_1 to

[1] See p. 209.

discharge. The small gap, which is platinum tipped, can be set with extreme accuracy, and the arrangement combines the advantage of very close setting, with a long air gap, since, as soon as the line current attempts to follow, after the discharge has taken place, the arc is speedily broken.

Besides the gaps already described, there is another form which has been very largely used, particularly, in America, namely, the non-arcing **multi-gap arrangement**, due originally to Wurts. He found that if a spark passed between two fairly massive cylinders, the tendency to form an arc was very much reduced. The action appears to be two-fold. In the

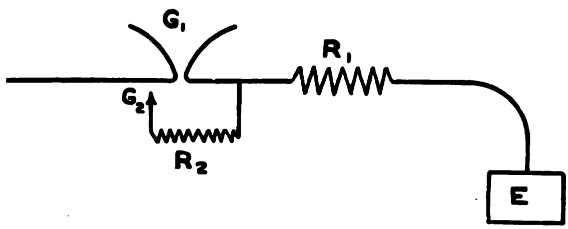


FIG 118.—Zapf horn arrester.

first place, the mass of metal cools down the arc to such an extent that it cannot be maintained, and also, there is probably an action somewhat similar to that taking place in a horn arrester, which tends to drive the arc towards the outer and wider parts of the gap, and so helps to break it. Some metals are said to give much more satisfactory results than others, but there seems some doubt as to whether much importance can be attached to this. As a further precaution, it is usual to place a number of cylinders in series, so as to break up the arc into several short lengths, and it is found that owing to a concentration of potential (see p. 202) the cylinders become charged up successively, so that the aggregate gap can be made much longer than the voltage could spark across, if a single gap were used. It will be clear that such a series of

gaps will not retain their non-arcing properties if too large a current is passed through them, and to limit this, a resistance is generally connected in series. The left-hand diagram in Fig. 119 shows such an arrangement, the cylinders being some $\frac{7}{8}$ inch in diameter, and the gaps about $\frac{1}{32}$ inch in length.

It is found, particularly with very high pressures, that the breaking-down voltage is much affected by the presence of earthed conductors, such as walls, buildings, etc., in the

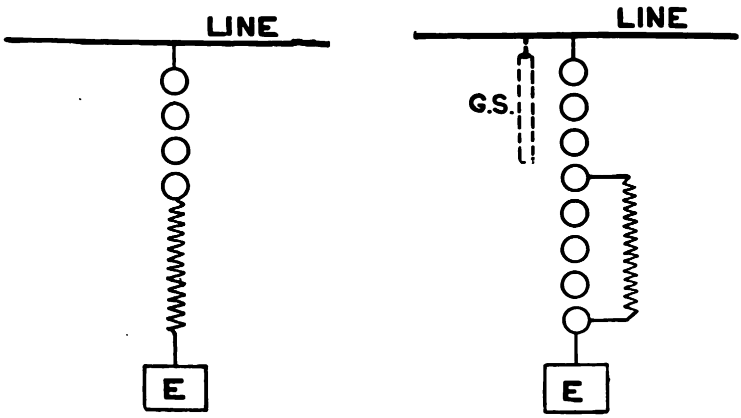


FIG. 119.—Multigap arresters.

neighbourhood of the gaps, owing to an uneven distribution of potential along the cylinders. To overcome this, a "**ground shield**" is employed, consisting of a metal conductor, connected to the line, and placed between the end cylinders and the disturbing conductor. This is shown in dotted lines at $G\ S$ in Fig. 119.

The arrangements so far described are of little use in dealing with lightning, owing firstly to the very large amount of energy which has to be got rid of, almost instantaneously, and secondly, to the enormous frequency of the discharge, which is so great (from 500,000 to 1,000,000 cycles per second)

that the **impedence of conductors** is such as to cause the discharge to take almost any path in preference to that offered by the resistance. In the case of a multi-gap arrester this difficulty is met by placing a number of gaps in parallel with the earth resistance, as shown in the right-hand diagram of Fig. 119. A lightning discharge passes to earth over all the gaps in series, while the line current is unable to do so, and the arc is broken. The objection to this arrangement is that a heavy discharge is liable to permanently damage the cylinders.

A more durable device consists of a horn arrester, similar to that shown in Fig. 117, but with the horns set very much further apart, and without any resistance to earth. The objection has been raised to the use of such arresters without resistances, that the breaking of the arc is liable to set up surges of its own in the circuit, so that "the cure is worse than the disease." This point of view may be reasonable enough, but on the other hand, experience shows that almost every other kind of arrester is liable to be destroyed by a severe lightning discharge (as distinguished from a mere surge) and that the line must be relieved from the severe strain at all costs.

The **best all-round system** would appear to consist of a fairly closely set and accurately adjustable horn gap, at the station, in series with a Brazil powder resistance (see page 210) and connected just outside the choking coils; a number of wider gap horn arresters being connected direct to earth, at intervals along the line. By this means the ordinary surges, which represent nine-tenths of the disturbances, are dealt with by the resistance gaps, while the more serious lightning discharges are carried direct to earth by the others, and, should the breaking of the comparatively large current which accompanies it cause abnormal surging, the remaining arresters are able to deal with this quite easily.

It is well to distribute the arresters as much as possible along the line owing to the fact that surges, being undulatory,

may give a "**Node,**" or point of zero potential, just at the particular spot where the arrester is situated.

The following table will serve as a guide in the **setting of horn arresters**:—

Normal line voltage ..	7,000	10,000	15,000	20,000	30,000
Suitable gap for use in series with a resistance.	3 m/m	5 m/m	8 m/m	12 m/m	21 m/m
Ditto, without resistance.	8 m/m	13 m/m	23 m/m	40 m/m	145 m/m

The construction of a **reliable resistance** is a matter of very considerable difficulty, owing to the large amount of energy to be dissipated during the comparatively short time (probably from 1 to 10 seconds) that the discharge lasts. **Rods** consisting of a mixture of carbon, or carborundum, and clay, were at one time much used, but, while quite satisfactory as regards heat dissipation, the resistance is found to increase in an erratic manner under the influence of repeated high-tension discharges, until, at last, the resistance breaks down altogether.

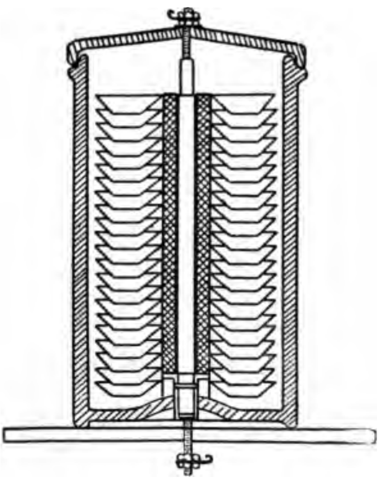


FIG. 120.—Electrolytic arrester.

The choice then lies between—

(1) A **wire resistance immersed in oil,** the chief objections to which are expense, limited heat capacity in the case of sudden discharges, owing to the small gauge of wire

necessarily used, difficulty of insulation and chance of fire owing to the oil.

(2) A **water resistance**, the objections to which are liability to dry up, unless constantly attended to, and sudden changes in resistance, owing to impurities getting into the water.

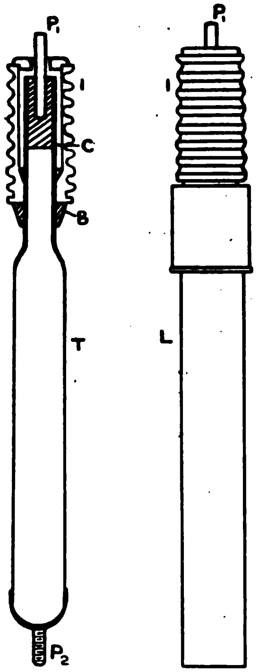


FIG. 121.—Moscicki condenser.

(3) A **powder resistance**, consisting of a column of carbon or carborundum powder, either compressed in a long vertical tube, by means of a weight at the top or, in Mr. H. **Brazil's pattern**,[1] laid in a zig-zag groove, in a fire-clay slab, about 8 inches square. The objection to the vertical column is that, owing to heating on the passage of a discharge, the powder becomes compressed, and the resistance of the whole permanently altered, whereas, in Mr. Brazil's arrangement, this is avoided, and, moreover, the heat capacity is much increased.

(4) A number of **electrolytic cells** in series. This device appears to have been suggested independently by several engineers, one of the first being Mr. Ferranti. It has been developed to some extent in America,[2] and one form is shown in Fig. 120. The plates or dishes are of aluminium, which has the well-known property of forming, when immersed in certain electrolytes, an almost insulating film on its surface; and, by special treatment, this film can be made to withstand as much

[1] See paper by W. H. Patchell, *Jl. Inst. E.E.*, Vol. 36, Part 176 (December, 1905).

[2] See Paper by J. S. Peck, before Inst. E.E., January, 1908.

as 400 volts per cell. When once pierced, the resistance falls to a negligible quantity, but so soon as the applied voltage falls below a certain critical value, the numberless small holes through which the discharge has passed, close up automatically, and the line current cannot follow over. The chief objection to this arrangement lies in the risk of the evaporation of the liquid, which would render the resistance useless, and in the difficulty of maintaining the insulation owing to creeping of the electrolyte.

The suggestion has several times been made, of connecting **condensers** between the lines and the earth, as a ready means of conducting away the charges. Their use depends upon the fact that the frequencies to be dealt with are so great as to enable comparatively small capacities to pass the heaviest discharges, almost instantly, whilst at the low frequency of supply the leakage is insignificant.

M. Moscicki has given a great deal of attention to this arrangement, and has designed a special condenser for the purpose. This is shown in Fig. 121, and consists of a tubular glass flask (*T* in the left-hand Fig.) which is thickened up towards the edge, as seen at *C*, since experience shows that condensers almost invariably break down near the edge. Both inside and out, the tube is given a coating of silver, protected by a deposit of copper. The whole is placed in a metal tube *L*, with which the outer coating is in contact at P_2, the space between being filled with a mixture of glycerine and water, to increase the cooling effect. The upper end of the metal case is closed in by a rubber plug *B*, and the insulator *I* carries the terminal P_1, connected to the inner coating of the condenser.

Fig. 122 shows the arrangement of such condensers on a three-wire three-phase system. *C C C* are three choking coils connected in the lines, while the condensers are shown at *c*. The three air gaps G_1, G_2, G_3, are so set that an

increase of 10 per cent. or 20 per cent. in pressure will cause a spark to pass to earth through the high resistances *R*. So soon as this happens, the oscillations thereby set up cause resonance in the circuit, consisting of two condensers and an air gap, at a frequency of something like 3,000,000 cycles per second. At this frequency the current which passes through

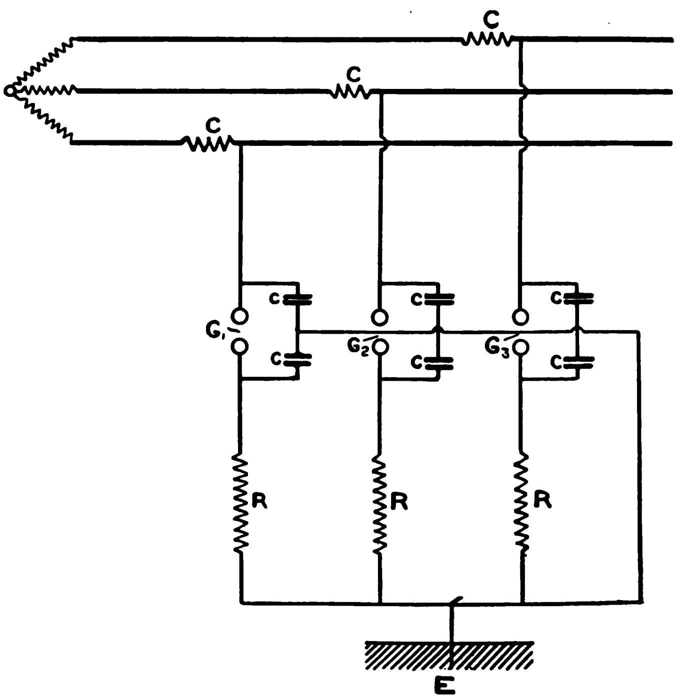


FIG. 122.—Condensers on a three-phase system.

the condenser is enormous, with the result that the line is almost instantly discharged. This applies to static charges also, but it is usual further to protect the lines by a resistance, or better still, a choking coil, connected between each conductor and the earth at some central point of the line.

The following **general considerations** should be borne in

mind in connection with the installation of lightning arresters. Where a **choking coil** is installed between the line and the generators, the arrester must be connected on the *line* side of it, as indicated in Fig. 117. The **path to earth** should be as straight as possible, so as to be free from self-induction, and any necessary bends should be of large radius. All joints in the earth connection must be most carefully soldered and protected, the conductor itself being not less than $\frac{1}{30}$ square inch in area. The **earth plate** should consist either of copper or iron, some 10 square feet in area, and at least $\frac{1}{8}$ inch thick. It should be buried deep enough to lie, as far as possible, in damp soil, a layer of a few inches of powdered coke being placed above and below it. Where a water-pipe or other metal system is available, connection should be made to this also. In the case of **arresters fixed on poles,** an iron pipe provided with a spike at its lower end is often driven into the ground, and serves as the earth connection, while, on **tramway and railway systems,** it is usual, as a further precaution, to connect the ground wire to the rails.

As regards the **number of arresters to be installed,** in addition to those at the station, this depends so largely on circumstances that no general rules can well be laid down. Perhaps the most difficult systems to protect are railways in exposed situations, since, in the first place, the lines and plant are usually designed to withstand only moderate pressures, and, moreover, the plant, consisting of trains or cars, is scattered at intervals along the line, and is difficult to protect adequately. In such cases, from five to seven per mile may be considered average practice, arresters being also fitted on each car. For transmission lines, from two to four per mile will usually be sufficient, an additional arrester being fixed at all points where plant is installed.

MISCELLANEOUS APPARATUS.

VOLTAGE AND CURRENT ALARMS.

It is often useful to have some signal to show when the voltage or current is above, or below, a certain predetermined value. The relays shown in Figs. 109 and 110 can be arranged to do so roughly, say within ± 10 per cent., but a much closer regulation than this is generally required. For **direct-current** working, a moving-coil voltmeter forms the most

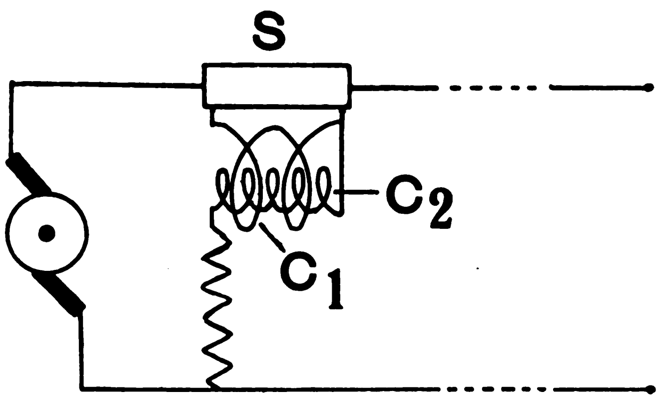


FIG. 123.—Compensated voltmeter.

convenient instrument, the pointer being provided with two platinum points, so arranged that, when the voltage falls, contact is made on one side, and when it rises, on the other. By this means, either a lamp can be lighted, or a bell rung, a regulation to within ± 1 per cent. being possible.

If the current to be carried by the contact exceeds, say, $\frac{1}{10}$ ampere, mercury cups, having a thin layer of oil on the top to prevent oxidation, are preferable, as the platinum contacts have a tendency to chatter and spark.

With **alternating current**, for which purpose a moving-iron, dynamometer or induction movement is usually employed,

this chattering is aggravated to such an extent that mercury contacts are almost essential.

COMPENSATED VOLTMETERS.

The voltage which the central station engineer really wishes to know is not so much that on the 'bus-bars, as **at the end of the feeders**, and, for this purpose, compensated

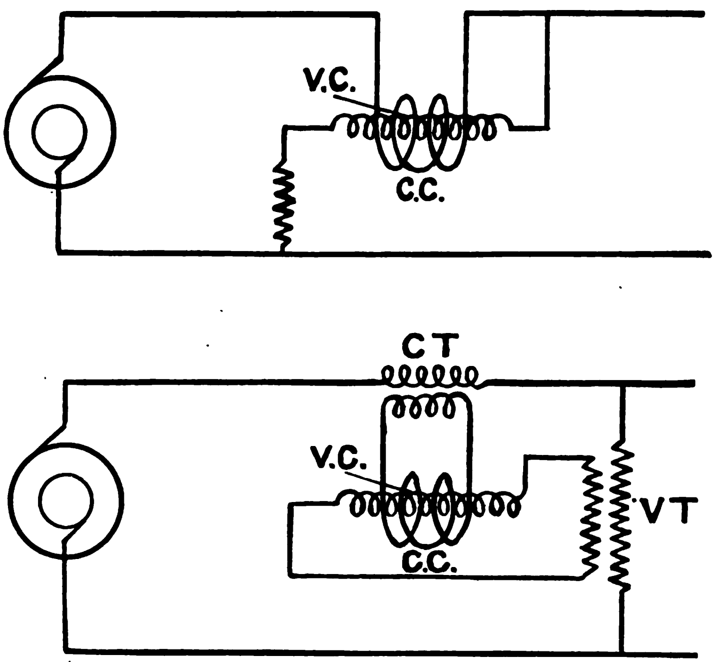


FIG. 124.—Compensated voltmeters.

voltmeters are often employed. A convenient arrangement for **direct current** is shown in Fig. 123. A moving-coil instrument, having two coils (C_1 and C_2), wound in opposition, is connected up as shown, one coil being joined across a shunt (S) and the other across the 'bus-bars. The number of turns on

the two coils is so proportioned that, with no current flowing through C_1, the instrument indicates the 'bus-bar voltage V, and with A amperes flowing it indicates $V\text{-}AR$, where R is the sum of the resistances of the two mains up to the feeding point. The drop in volts along S being proportional to A, it will be seen that this relation holds good for all currents. The value of R will vary slightly from day to day according to the temperature, but, in the case of underground mains, the variation is not large. Fig. 124 shows a similar arrangement suitable for an **alternating-current** feeder, both with and without current and voltage transformers (CT and VT). The instrument, which may be of either the moving-iron or induction pattern, has an ordinary volt-winding (VC) and a few back turns (CC) carrying the main current, or a current proportional to it. By suitably choosing the relative number of turns, the instrument can, as before, be made to read $V\text{-}AR$, on the assumption that the load is non-inductive. If the current and voltage are out of phase by an angle, ϕ, the reading will be $V\text{-}AR \cos \phi$, instead of $V\text{-}AR$.

This objection can be overcome by causing the two coils CC and VC to act on different parts of the induction disc, or on two separate irons mechanically connected. The instrument will then read the true difference, independently of the power factor of the circuit.

THE CYMOMETER.

Dr. J. A. Fleming has designed an instrument which, although primarily intended for the measurement of wavelengths and frequency, in connection with wireless telegraphy, is of considerable value in the **measurement of small inductances and capacities**. Its use in connection with these latter measurements alone comes within the scope of the present volume. The **instrument consists**, primarily,

of an air-cored wire coil (*F*, Fig. 125) in series with a condenser, consisting of inner and outer metal tubes (*C* and *E*), which form the two plates. If a conductor (a portion of which is shown at *G H*) carrying a high frequency current is placed near the straight wire *A B*, a high frequency E.M.F. will be induced in the latter, and, if the **oscillation constant** of the cymometer is tuned to this frequency, resonance will occur, and a high E.M.F. will exist across the condenser. The oscillation constant is adjustable, within a range of about 25 to 1, by sliding the outer tube of the condenser more or

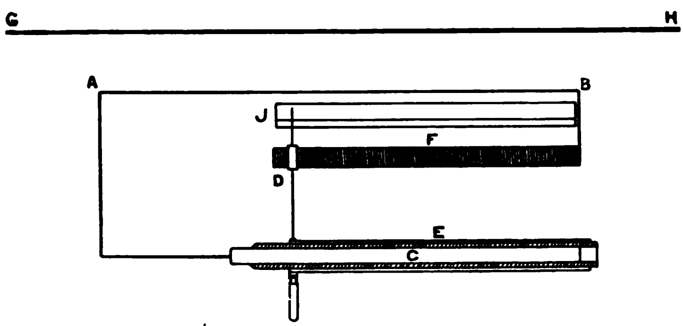


FIG. 125.—The Fleming cymometer.

less off the inner one, thereby reducing the capacity, and at the same time sliding the contact *D*, which is rigidly attached to E, along the spiral *F*, thus cutting out more or less of the self-induction.

The frequency to which a circuit responds is proportional to the "oscillation constant" (*i.e.*, to $\sqrt{C \times I}$, where *C* is the capacity in micro-farads, and *I* the self-induction in centimetres). So that, by varying *C* and *I* simultaneously, a considerable range of adjustment is possible. The most generally useful range is that in which $\sqrt{C \times I}$ can be varied, say, from 1 to 20. The point of maximum resonance is determined by connecting a vacuum tube across the condenser

EC, and noting the position of maximum brightness; the oscillation constant can then be read off the scale *J*, and, this being known, the frequency to which the circuit responds is also known.

MEASUREMENT OF SMALL CAPACITIES.

Fig. 126 gives the connections for this purpose, a Leyden jar being shown. The induction coil (*A*) is arranged to spark between two balls (*B*), across which are connected a known inductance (*D*), in series with the condenser under test (*C*). The frequency of the oscillations in this circuit will depend on

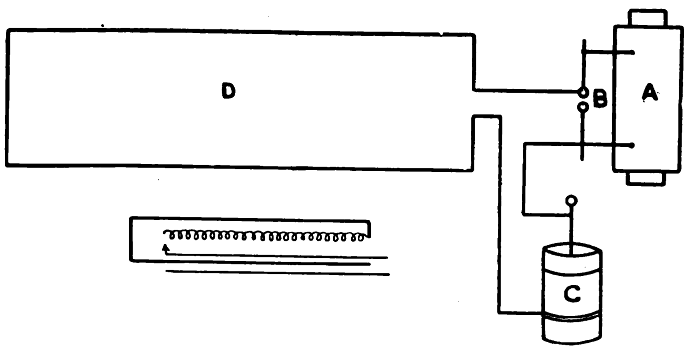


FIG. 126.—Measurement of capacity by the cymometer.

its oscillation constant, and if the Cymometer is placed so that the wire *A B* (Fig. 125) is parallel to one side of the known inductance *D*, both the frequency and the oscillation constant can be read off on the scale. Now the constant of the circuit containing *D* and *C* will be the same as that of the Cymometer, for resonance to occur, and consequently, the self-induction being known, the capacity can be calculated thus:—

$$\text{Capacity of the jar} = \frac{(\text{constant})^2}{\text{inductance in centimetres}}.$$

The Cymometer is suitable for measuring capacities up to say, 0·05 micro-farad in this way.

MEASUREMENT OF SMALL INDUCTANCES.

Determine, as just described, the capacity (C) of a small Leyden jar, and then connect the inductance to be measured in series with C and D (Fig. 126). Let the known inductance be I_1, and the unknown I_2; the measured capacity of the Leyden jar C and the oscillation constant, with and without I_2, be K_2 and K_1 respectively, then—

$$I_1 = \frac{K_1^2}{C}, \text{ and } I_1 + I_2 = \frac{K_2^2}{C_1},$$

$$\therefore \quad I_2 = \frac{K_1^2}{C} - \frac{K_2^2}{C} = \frac{K_1^2 - K_2^2}{C}.$$

In this way, small self-inductions up to, say, 0·1 millihenry can be readily measured by means of the Cymometer, whereas their satisfactory measurement by other methods is somewhat difficult.

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THE END.

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